

APPARATUS AND METHOD FOR
OPTICAL ADD/DROP MULTIPLEXING

RELATED APPLICATIONS

This application claims is related to Application Serial Number _____, entitled "Apparatus and Method for Controlling Polarization of An Optical Signal," filed on December ___, 2000; to Application Serial Number _____, entitled "Apparatus and Method for Controlling Polarization of an Optical Signal," filed on December ___, 2000; and to Application Serial Number _____, entitled "entitled "Apparatus and Method for Providing Gain Equalization," filed on December ___, 2000.

TECHNICAL FIELD OF THE INVENTION

15 The present invention relates to the field of communication systems, and more particularly to an apparatus and method for facilitating optical add/drop multiplexing.

Various techniques for facilitating optical add/drop multiplexing have been developed. However, none of the previous approaches has provided a satisfactory solution to the problem of add/drop multiplexing optical signals carrying numerous - sometimes hundreds - of wavelength components. In those situations, the cost of fabricating conventional devices to process each wavelength in the signal quickly becomes prohibitive.

SUMMARY OF THE INVENTION

The present invention recognizes a need for a method and apparatus operable to economically facilitate add/drop multiplexing, particularly in signals carrying multiple wavelengths.

In one aspect of the invention, an apparatus operable to facilitate add/drop multiplexing of optical signals comprises an input operable to receive an input optical signal and an added optical signal, the input operable to generate a first and a second copy of the input signal and a first and a second copy of the added signal. The apparatus further comprises a plurality of at least substantially reflective surfaces, each operable to receive either the first signal copies or the second signal copies and to reflect the copies for ultimate combination at an output to form an output signal for transmission. At least one of the at least substantially reflective surfaces comprises a moveable mirror operable to change its position relative to the input to create a phase shift between the first and second signal copies so that either the input optical signal or the added optical signal is communicated as the output signal depending on the position of the at least one moveable mirror.

In another aspect of the invention, an apparatus operable to facilitate add/drop multiplexing of optical signals comprises a drop phase shift stage operable to receive an input optical signal and to either drop the input signal or to pass the optical signal toward an output, the drop phase shift stage comprising an at least substantially reflective surface operable to change its position to affect whether the input signal is dropped or

passed to the output. The apparatus further comprises an add phase shift stage operable to receive and communicate as an output either an added signal or the input signal passed from the drop phase shift stage, the add phase shift stage comprising an at least substantially reflective surface operable to change its position to affect whether the added signal or the input signal is passed to the output.

In still another aspect of the invention, a wave division add/drop multiplexer comprises a wavelength division demultiplexer operable to separate an optical input signal into a plurality of wavelengths and an array of optical add/drop multiplexers coupled to the demultiplexer. At least one add/drop multiplexer of the array comprises an input operable to receive an input wavelength signal and an added wavelength signal, and to generate a first and a second copy of the input signal and a first and a second copy of the added signal. The system further comprising a plurality of at least substantially reflective surfaces, each operable to receive either the first signal copies or the second signal copies and to reflect the copies for ultimate combination at an output to form an output signal for transmission. At least one of the at least substantially reflective surfaces comprises a moveable mirror operable to change its position relative to the input to create a phase shift between the first and second signal copies so that either the input optical signal or the added optical signal is communicated as the output signal depending on the position of the at least one moveable mirror. The system further comprises a wavelength division

09745832 132200
00000000 2284760

multiplexer operable to receive a plurality of output signals from the array of add/drop multiplexers and to multiplex at least some of the output wavelengths into an optical output signal.

5 In yet another aspect of the invention, a wave division add/drop multiplexer comprises a wavelength division demultiplexer operable to separate an optical input signal into a plurality of wavelengths and an array of optical add/drop multiplexers coupled to the
10 demultiplexer. At least one of the add/drop multiplexers comprises a micro-electro-optic system (MEMS) device including a moveable mirror layer operable to undergo a substantially piston-like motion to create a phase difference between a wavelength reflected from the
15 moveable mirror layer and a substantial copy of that wavelength, the position of the moveable mirror layer affecting whether the input wavelength is passed through or dropped from the array. The wavelength division add/drop multiplexer further comprises a wavelength
20 division multiplexer operable to receive a plurality of output wavelengths from the array and to multiplex at least some of the output wavelengths into an optical output signal.

In still another aspect of the invention, a wave
25 division add/drop multiplexer comprises a wavelength division demultiplexer operable to separate an optical input signal into a plurality of wavelengths and an array of optical add/drop multiplexers coupled to the demultiplexer. At least one of the add/drop multiplexers
30 comprises a drop phase shift stage operable to receive an input wavelength and to either drop the input wavelength

002221 228460

or to pass the input wavelength toward an output, the drop phase shift stage comprising an at least substantially reflective surface operable to change its position to affect whether the input wavelength is
5 dropped or passed to the output. At least one of the add/drop multiplexers further comprises an add phase shift stage operable to receive and communicate as an output either an added wavelength or the input wavelength passed from the drop phase shift stage, the add phase
10 shift stage comprising an at least substantially reflective surface operable to change its position to affect whether the added wavelength or the input wavelength is passed to the output. The wave division add/drop multiplexer further comprises a wavelength
15 division multiplexer operable to receive a plurality of output wavelengths from the add phase shift stage and to multiplex at least some of the output wavelengths into an optical output signal.

In another aspect of the invention, a method of
20 facilitating optical add/drop multiplexing comprises receiving an input optical signal and an added optical signal, generating a first and a second copy of the input signal, and generating a first and a second copy of the added signal. The method also comprises communicating
25 the first signal copies toward a first mirror and the second signal copies toward the second mirror, and changing the position of the first mirror to create a phase shift between the first and second copy when combined at an output. The method still further
30 comprises communicating either an added signal or the

input signal as an output signal depending at least in part on the position of the first mirror.

In yet another aspect of the invention, a method of facilitating optical add/drop multiplexing comprises receiving an optical input signal at a first stage, generating a first and a second copy of the input signal, and communicating the first signal copy toward a first mirror and the second signal copy toward the second mirror. The method further includes changing the position of the first mirror to create a phase shift between the first and second copy when combined at an output of the first stage and communicating either an added signal or the input signal from the first stage toward a second stage depending at least in part on the position of the first mirror. In addition, the method comprises generating a first and a second copy of the signal received at the second stage and communicating the first received signal copy toward a third mirror and the second received signal copy toward a fourth mirror. The method still further includes changing the position of the third mirror to create a phase shift between the first and second received signal copies when combined at the second output, and communicating either the added signal or the input signal from the first stage from the second output depending at least in part on the position of the third mirror.

In still another aspect of the invention, a method of facilitating wave division add/drop multiplexing, comprises receiving an optical input signal comprising a plurality of wavelengths, separating the optical signal into a plurality of wavelength signals, and communicating

09746822.1 22200

at least some of the wavelength signals to an array of optical add/drop multiplexers. At at least one of the add/drop multiplexers, the method comprises receiving an input optical signal and an added optical signal,
5 generating a first and a second copy of the input signal, generating a first and a second copy of the added signal, and communicating the first signal copies toward a first mirror and the second signal copies toward the second mirror. The method further comprises changing the
10 position of the first mirror to create a phase shift between the first and second copy when combined at an output, and communicating either an added signal or the input signal as an output signal depending at least in part on the position of the first mirror.

15 In another aspect of the invention, a method of facilitating wave division add/drop multiplexing comprises receiving an optical input signal comprising a plurality of wavelengths, separating the optical signal into a plurality of wavelength signals, and communicating
20 at least some of the wavelength signals to an array of optical add/drop multiplexers. At at least one of the add/drop multiplexers, the method comprises receiving an optical input signal at a first stage, generating a first and a second copy of the input signal, and communicating
25 the first signal copy toward a first mirror and the second signal copy toward the second mirror. The method further comprises changing the position of the first mirror to create a phase shift between the first and second copy when combined at an output of the first
30 stage, and communicating either an added signal or the input signal from the first stage toward a second

09246321 13220

Depending on the specific features implemented,
15 particular embodiments of the present invention may
exhibit some, none, or all of the following technical
advantages. One aspect of the invention facilitates
add/drop multiplexing using a minimal number of
components, thereby minimizing the cost of the system.
20 Another aspect of the present invention provides an
effective and cost efficient mechanism for facilitating
optical add/drop multiplexing, particularly in a multiple
wavelength optical communication system. In a particular
embodiment, implementing MEMS based phase shift stages
25 facilitates fabrication of arrays of these devices at an
incremental additional cost to fabricating a single phase
shift stage. This aspect of the invention provides
significant advantages in facilitating rapid, effective,
and economical add/drop multiplexing, particularly in an
30 environment supporting numerous wavelengths.

In addition, particular embodiments of the invention allow for bypass of various wavelengths without requiring processing of those wavelengths. This feature can be particularly useful in metropolitan systems, which use some of the multiple wavelengths carried in the optical signals, but perhaps not every wavelength in the signal. This feature, therefore, permits bypassing unused wavelengths to save system resources and expense.

Other technical advantages are readily apparent to one of skill in the art from the attached figures, description, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and for further features and advantages thereof, reference is now made to the following
5 description taken in conjunction with the accompanying drawings, in which:

FIGURE 1a is a block diagram of an exemplary embodiment of an apparatus operable to provide high speed optical signal processing according to the teachings of
10 the present invention;

FIGURE 1b is a block diagram showing an exemplary geometry associated with one embodiment of an apparatus operable to provide high speed optical signal processing according to the teachings of the present invention;

15 FIGURES 1c-1d are block diagrams showing other exemplary embodiments of apparatus operable to provide high speed optical signal processing according to the teachings of the present invention;

FIGURES 2a-2d are block diagrams of various
20 embodiments of apparatus operable to provide high speed optical signal processing according to the teachings of the present invention;

FIGURES 3a-3c are block diagrams showing a plurality of views of various embodiments of moveable mirrors
25 operable for use with the apparatus described in FIGURES 1 and 2 and constructed according to the teachings of the present invention;

FIGURE 4 is a block diagram of one embodiment of a variable attenuator constructed according to the
30 teachings of the present invention;

09745823 13300
002227 228460

FIGURE 5b is a block diagram of one embodiment of a two-by-two switch constructed according to the teachings of the present invention;

FIGURE 6 is a flowchart showing one example of a method of facilitating optical signal processing according to the teachings of the present invention;

FIGURES 7a-b are block diagrams showing various
embodiments of polarization controllers constructed
15 according to the teachings of the present invention;

FIGURE 7c is a graph showing example switching speeds associated with one particular embodiment of the invention;

FIGURES 8a-8h are block diagrams showing various
20 embodiments of systems implementing polarization mode
dispersion (PMD) compensators, PMD compensator designs,
and components suitable for use in PMD compensators
constructed according to the teachings of the present
invention;

25 FIGURE 9 is a flowchart showing one example of a
method of controlling the polarization of an optical
signal and of mitigating polarization mode dispersion
according to the teachings of the present invention;

FIGURES 10a-10b are block diagrams showing a system
30 and components thereof operable to mitigate polarization
mode dispersion in optical signals having multiple

wavelengths according to the teachings of the present invention;

05/15/2006 12:22:00

FIGURE 11 is a flowchart showing one example of a method of mitigating polarization mode dispersion of optical signals having multiple wavelengths according to the teachings of the present invention;

5 FIGURE 12 is a block diagram showing an exemplary embodiment of a polarization multiplexing system constructed according to the teachings of the present invention;

10 FIGURE 13 is a block diagram of an exemplary system operable to facilitate coherent optical communication according to the present invention;

15 FIGURE 14a is a block diagram of an exemplary embodiment of a multiple channel communication system having gain equalization capabilities constructed according to the teachings of the present invention;

FIGURE 14b is a block diagram of another exemplary embodiment of a multiple channel communication system having gain equalization capabilities constructed according to the teachings of the present invention;

20 FIGURE 14c is a block diagram of an exemplary gain equalizer suitable for use in a single or multiple band communication system and constructed according to the teachings of the present invention;

25 FIGURE 15 is a flowchart showing one example of a method of facilitating gain equalization of a plurality of wavelengths according to the teachings of the present invention;

30 FIGURE 16a is a block diagram showing one embodiment of an exemplary wave division add/drop multiplexer architecture constructed according to the teachings of the present invention;

09/46/23 12:20:00

FIGURES 16b-16c are block diagrams showing various example embodiments of add/drop multiplexers constructed according to the teachings of the present invention;

FIGURE 16d is a block diagram showing a plurality of
5 add/drop multiplexers as shown in FIGURE 10b arranged to collectively form a wave division add/drop multiplexer according to the teachings of the present invention; and

FIGURE 17 is a flowchart showing one example of a method of facilitating add/drop multiplexing of optical
10 signals according to the teachings of the present invention.

09746823 122200
000000 22894260

DETAILED DESCRIPTION OF THE INVENTION

I. Building Blocks for High Speed Optical Signal Processing

FIGURE 1a is a block diagram of one exemplary
5 embodiment of an apparatus 10a operable to provide high
speed optical signal processing. Throughout this
document, the term "signal processing" includes
attenuation, switching, phase shifting, polarization
control, mitigation of polarization mode dispersion, or
10 any other manipulation of one or more optical signals.

Apparatus 10a includes a beam splitter 20a, which
communicates with mirrors 30a and 40a. Beam splitter 20a
may comprise any structure or combination of structures
operable to pass a first copy of an optical signal in one
15 direction and a second copy of the optical signal in
another direction. For example, in a particular
embodiment, beam splitter 20a may comprise a partially
silvered mirror. As another example, beam splitter 20a
may comprise a mirror having one or more layers of a
20 dielectric coating. As still another example, beam
splitter 20a may comprise a fiber coupler.

Throughout this document, the terms "copy" and
"signal copy" are used to describe optical signals that
are at least substantial copies of the input optical
25 signal, each having at least substantially equal
quantities of wavelengths as the other. Depending on the
type of beam splitter used to create the multiple signal
copies, the two copies may or may not have equal
intensities. For example, a 50/50 beam splitter will
30 generate two substantially identical copies of the input
signal — substantially equal in content and intensity.

Other types of beam splitters, however, may create uneven distributions of intensities in the resulting signal "copies." Beam splitters having various ratios other than 50/50 could be used consistent with the present invention. However, an approximately 50/50 beam splitter typically provides a good contrast ratio by maintaining the optical symmetry of a physically symmetrical device.

Apparatus 10a includes a plurality of mirrors, in this case a first mirror 30a and a second mirror 40a. Throughout this document, the term "mirror" refers to an at least substantially reflective surface or collection of surfaces. At least one of mirrors 30a and 40a comprises a moveable at least substantially reflective surface or collection of surfaces. In this example, second mirror 40a comprises a fixed mirror structure. The location of second mirror 40a relative to beam splitter 20a does not change during operation of the device. In this embodiment, first mirror 30a, however, comprises a moveable mirror layer of a micro-electro-optic system (MEMS) device operable to be displaced anywhere between positions 32a and 34a. Movement of first mirror 30a can be, for example, in response to a control signal, such as a control voltage. Although this embodiment includes just one moveable mirror, apparatus 10a could alternatively comprise additional moving mirrors. Some embodiments of apparatus using multiple moving mirrors will be described below.

In the illustrated embodiment, first copy 62a of input optical signal 60a meets first mirror 30a at a grazing angle THETA. In a similar manner, second copy 64a of signal 60a meets second mirror 40a at

approximately angle THETA. In the example shown in FIGURE 1, angle THETA comprises approximately forty-five degrees. Other grazing angles could be used without departing from the scope of the invention. In addition,
5 mirrors 30a and 40a could receive first and second signal copies 62a and 64a at different angles from one another without departing from the present invention. Maintaining symmetry between the arms of the device, however, provides an advantage of increasing the contrast
10 ratio at the device's output.

In this particular embodiment, apparatus 10a further includes a beam splitter 50a operable to receive first copy 62a and second copy 64a of input signal 60a, after those signals have been reflected off of mirrors 30a and
15 40a, respectively. Beam splitter 50a combines components of first copy 62a and second copy 64a of input signal 60a to result in first output signal 72a and second output signal 74a. Beam splitter 50a can be similar in structure and function to beam splitter 20a described
20 above. In some embodiments (described more fully below), beam splitters 20a and 50a could comprise locations on a single beam splitting device.

In the illustrated embodiment, first and second mirrors 30a and 40a are separated from beam splitter 20a
25 by a distance (d). Apparatus 10a can introduce a difference (DELTA d) in signal path (d) by moving first mirror 30a in an at least substantially piston-like motion by a distance DELTA L. Throughout this document, the term "piston-like" motion refers to a motion in which
30 the moveable mirror is intended to be displaced in an approximately parallel plane to the previous mirror

position. In other words, a "piston-like" motion is intended to substantially maintain the grazing angle THETA between at least a portion of the moveable surface of first mirror 30a and first signal copy 62a. Moving
5 the mirror layer 30a in a substantially piston-like motion to substantially maintain the grazing angle THETA results in an advantage of reducing signal dispersion when the signal copies are combined.

In practice, for various reasons, physical
10 embodiments of the invention may not exhibit true "piston-like" motion, although such embodiments are intended to be within the scope of the invention. For example, the moveable mirror layer may be anchored at its ends and may exhibit some curvature between the anchor
15 points as it moves from one position to another. In addition, variances in resistance across the moveable mirror layer may result in one portion of the moveable mirror layer experiencing more movement than another portion. The invention is intended to encompass these
20 embodiments within the definition of "piston-like" motion.

FIGURE 1b is a block diagram showing an exemplary geometry associated with one embodiment of an apparatus operable to provide high speed optical signal processing
25 according to the present invention. Line 32' in FIGURE 1b represents a position of first mirror 30a that would provide a distance (d) between beam splitter 20a and first mirror 30a residing at a first position 32'. Line 32a shows a modified position of first mirror 30a after a
30 piston-like movement resulting in a displacement of DELTA L from position 32a'.

09746837 122000

As shown in FIGURE 1b, moving first mirror 30a from position 32a' to position 32a by distance DELTA L creates a difference of DELTA d in the length of the signal path of first signal copy 62a. This difference in signal path translates to a difference in phase between first signal copy 62a and second signal copy 64a of input signal 60a. The phase difference between first and second copies 62a and 64a results in an interference, which alters the amplitude of output signal 72a relative to that of input signal 60a.

In operation, because first copy 62a of input signal 60a travels a different signal path length than second copy 64a of input signal 60a, a phase difference between the two signal copies results in interference between the two signals when they are combined. For a given change in the signal path length, the amplitude of first output 72a is proportional to \cos^2 of one half of the phase difference PHI between signal copies 62a and 64a. In a similar manner, for a given change in the signal path length, the amplitude of second output 74a is proportional to \sin^2 of one half of the phase difference PHI between signal copies 62a and 64a.

FIGURES 1c and 1d show additional exemplary embodiments of apparatus operable to provide high speed optical signal processing. FIGURE 1c is a block diagram of an apparatus 10b, which operates in a similar manner to apparatus 10a, but uses a single beam splitting device 20b to comprise a first beam splitter operable to separate the input signal 60b into signal copies 62b and 64b, and a second beam splitter operable to combine

components of the reflected signal copies to form output signals 72b and 74b.

Beam splitter 20b communicates with a plurality of at least substantially reflective surfaces including mirrors 30b and 40b. Beam splitter 20b is similar in structure and function to beam splitters 20a and 50a discussed with respect to FIGURE 1a. As in apparatus 10a described with respect to FIGURE 1a, apparatus 10b includes at least one moveable mirror, in this case first mirror 30b. In this example, moving mirror 30b is similar in structure and function to first mirror 30a in FIGURE 1a. Apparatus 10b could include additional and/or other moving mirrors without departing from the scope of the invention.

Apparatus 10b also includes mirrors 90b and 80b operable to reflect signal copies 62b and 64b back toward beam splitter 20b, where components of the reflected signals can be combined to form output signals 72b and 74b.

In operation, apparatus 10b receives optical input signal 60b at beam splitter 20b. Beam splitter 20b communicates a first signal copy 62b toward first mirror 30b, and communicates a second signal copy 64b toward second mirror 40b. First mirror 30b is operable to be displaced by a distance ΔL to create a path length difference Δd between the signal path lengths of first signal copy 64a and second signal copy 64b. The difference in path length creates a phase difference between the signal copies, which results in a change in amplitude of the signal relative to input signal 60b. By selectively varying the position of, for example, first

00222T 2284260

mirror 30b, apparatus 10b can control the intensity of output signals 72b and 74b.

FIGURE 1d is a block diagram of another example configuration of an apparatus 10c operable to facilitate high speed optical signal processing. Apparatus 10c operates in a similar manner to apparatus 10a and 10b, but uses a single beam splitter 20c, and orients first and second mirrors 30c and 40c at ninety-degree grazing angles THETA.

Apparatus 10c includes a beam splitter 20c, which communicates with a plurality of at least substantially reflective surfaces including mirrors 30c and 40c. Beam splitter 20c is similar in structure and function to beam splitters 20a and 50a discussed with respect to FIGURE 1a. As in apparatus 10a described with respect to FIGURE 1a, apparatus 10c includes at least one moveable mirror, in this case first mirror 30c. In this example, moving mirror 30c is similar in structure and function to first mirror 30c in FIGURE 1a. Apparatus 10c could include additional and/or other moving mirrors without departing from the scope of the invention.

Apparatus 10c also includes a circulator 65c operable to receive input signal 60c and to communicate that signal to beam splitter 20c, while also receiving output signal 72c and communicating that signal away from the source of input signal 60c.

In operation, apparatus 10c receives optical input signal 60c at beam splitter 20c. Beam splitter 20c communicates a first signal copy 62c toward first mirror 30c, and communicates a second signal copy 64c toward second mirror 40c. First mirror 30c is operable to be

displaced by a distance DELTA L to create a path length difference DELTA d between the signal path lengths of first signal copy 64a and second signal copy 64b. The difference in path length creates a phase difference
5 between the signal copies, which results in a change in amplitude of the signal relative to input signal 60c. By selectively varying the position of, for example, first mirror 30c, apparatus 10c can control the intensity of output signals 72c and 74c.

10 The aggregate difference in signal path length (DELTA d) achieved for a given mirror displacement DELTA L can be improved in a variety of ways. FIGURES 2a-2c are block diagrams of various embodiments of apparatus operable to provide additional phase shift between signal
15 copies for a given per-mirror displacement.

Apparatus 100 shown in FIGURE 2a is similar in structure and function to apparatus 10a shown in FIGURE 1a, but includes moveable mirror elements in each arm of the device. Apparatus 100 includes a first beam splitter
20 120, which receives an input signal 160 and sends a first signal copy 162 toward a first mirror 130, and a second signal copy 164 toward a second mirror 140. First and second mirrors 130 and 140 reflect first and second signal copies 162 and 164 toward a second beam splitter
25 150. Second beam splitter 150 combines components of the reflected first and second signal copies 162 and 164 to form first output 172 and second output 174.

In this example, both first mirror 130 and second mirror 140 comprise moveable mirror structures. Each of
30 mirrors 130 and 140 is operable to move relative to the other to contribute to a difference in path length of the

002221" 2284450

signals received and reflected toward second beam splitter 150. Using multiple moving mirrors facilitates the same overall path difference with each mirror moving only a fraction of the distance ΔL . For example, where the angle θ is forty five degrees, for a desired total path difference of Δd , each of first and second mirrors 130 and 140 moves a distance $\Delta L/2$, each creating a path difference of $\Delta d/2$, combining for a total path difference of Δd .

As a particular example, first mirror 130 may move away from first beam splitter 120 from position 132 to position 134 to increase the path length of first signal copy 162 by $\Delta d/2$. Second mirror 140 may move toward first beam splitter 120 from position 144 to position 142 to decrease the path length of second signal copy 164 by $\Delta d/2$. The combined effect of the movement of first and second mirrors 130 and 140 is to create a total path difference of Δd , resulting in a desired phase difference and output intensity.

Implementing multiple moving mirrors provides an advantage of decreasing the displacement of each moving mirror. This, in turn, decreases the drive voltage necessary to operate each moving mirror, and increases the speed at which the position of the mirrors, and hence the intensity of the output signal, can be manipulated. Although apparatus 100 is described with respect to the configuration shown in FIGURE 1a, multiple moving mirrors could be similarly be implemented in other embodiments, such as those shown in FIGURES 1c-1d.

Another way to reduce the amount of displacement experienced by each moving mirror for a given level of

25

phase difference is to implement additional moving mirrors in each arm of the device. For example, FIGURE 2b shows an apparatus 110 having multiple moveable mirrors on each arm between the first beam splitter 120 and the second beam splitter 150.

Apparatus 110 shown in FIGURE 2b is similar in structure and function to apparatus 100 shown in FIGURE 2a and apparatus 105 shown in FIGURE 2a. Apparatus 110 includes a first beam splitter 120, which receives an input signal 160 and sends a first signal copy 162 toward a first mirror 130a, and a second signal copy 164 toward a second mirror 140a. First mirror 130a reflects first signal copy 162 toward a third mirror 130b that, in turn, reflects first signal copy 162 toward a fixed mirror 180 and on to second beam splitter 150. Similarly, second mirror 140a reflects second signal copy 164 toward a fourth mirror 140b that, in turn, reflects second signal copy 164 toward a fixed mirror 190 and on to second beam splitter 150. Second beam splitter 150 combines components of the reflected first and second signal copies 162 and 164 to form first output 172 and second output 174.

In this example, each of mirrors 130a-130b and mirrors 140a-140b comprises a moveable mirror structure. Each of mirrors 130a-130b and 140a-140b is operable to move to contribute to a difference in path length of the signals received and reflected toward second beam splitter 150. In addition, although mirrors 180 and 190 are shown as fixed mirrors, one or more of those mirrors could alternatively comprise moveable mirror structures.

Using multiple moving mirrors in each arm of device 100 facilitates an overall path difference L with each mirror moving only a fraction of the distance ΔL . For example, where the angle θ is forty five degrees, for a desired total path difference of Δd , each of first and second mirrors 130 and 140 moves a distance $\Delta L/4$, each creating a path difference of $\Delta d/4$, combining for a total path difference of Δd .

In a particular example, mirrors 130a-b may move from positions 132 to positions 134 to increase the path length of first signal copy 162 by $\Delta d/2$. Second mirrors 140a-b may move from positions 144 to positions 142 to decrease the path length of second signal copy 164 by $\Delta d/2$. The combined effect of the movement of first and second mirrors 130a-b and 140a-b is to create a total path difference of Δd , resulting in a desired phase difference and output intensity.

The embodiment shown in FIGURE 2b provides an advantage of further decreasing the necessary displacement of moveable mirrors 130 and 140. This decreases the drive voltage needed to move each mirror and increases the speed of the device. This concept also applies to other embodiments of the invention, including those shown in FIGURES 1c-1d.

Still another way to reduce the amount of displacement experienced by each moving mirror while still attaining a given level of phase difference is to reduce the grazing angle (θ) between signals 162 and 164 on first and second mirrors 130 and 140, respectively. In a particular embodiment, first and second beam splitters 120 and 150 form a rhombus with

first and second mirrors 130 and 140. Referring to
FIGURE 1b to illustrate, the path difference DELTA d can
be calculated as $\text{DELTA } d = \text{DELTA } L / \sin(\text{THETA})$. Reducing
the grazing angle THETA reduces the term $\sin(\text{THETA})$,
5 resulting in a greater path difference DELTA d for a
given change in mirror location represented by the
distance DELTA L.

Apparatus 115 shown in FIGURE 2c is similar in
structure and function to apparatus 100 shown in FIGURE
10 2a, and apparatus 110 shown in FIGURE 2b. Apparatus 115
includes a first beam splitter 120, which receives an
input signal 160 and sends a first signal copy 162 toward
a first mirror 130, and a second signal copy 164 toward a
second mirror 140. First and second mirrors 130 and 140
15 reflect first and second signal copies 162 and 164 toward
a second beam splitter 150. Second beam splitter 150
combines components of the reflected first and second
signal copies 162 and 164 to form first output 172 and
second output 174.

20 In this example, both first mirror 130 and second
mirror 140 comprise moveable mirror structures. Each of
mirrors 130 and 140 is operable to move relative to the
other to contribute to a difference in path length of the
signals received and reflected toward second beam
25 splitter 150. In the illustrated embodiment, for a
desired total path difference of DELTA d, each of first
and second mirrors 130 and 140 may move a distance DELTA
L, each creating a path difference of $\text{DELTA } L / \sin(\text{THETA})$,
combining for a total path difference of DELTA d. The
30 smaller the angle THETA, the larger the path difference
created for a given mirror displacement. Said another

09746833 123000
00000000 00000000

way, using mirrors at small grazing angles to signals 162 and 164, desired path differences can be created with smaller mirror displacements. This results in smaller drive voltages needed to move the mirrors, and faster
5 device operation.

Efficiency and speed advantages can be compounded by implementing combinations of the embodiments shown in FIGURES 2a-2c. For example, a desired phase difference can be introduced between signal copies 162 and 164 using
10 minimal mirror displacement by implementing multiple moving mirrors in each arm of the device, where one or more of the mirrors has grazing angle with the incoming signal that is less than forty five degrees.

FIGURES 3a-3c are block diagrams showing a plurality
15 of views of various embodiments of moveable mirrors suitable for use with the apparatus described in FIGURES 1 and 2. FIGURE 3a is a block diagram showing a movable mirror 130, which can be used in devices shown in FIGURES 2a-2d and describe above. In the particular example
20 shown in FIGURE 3a, movable mirror device 130a comprises a micro-mechanical electro-optical switching ("MEMS") device. MEMS device 130a includes a reflective conducting layer 135a disposed outwardly from an inner conductive layer 131a or 133a. Reflective conducting
25 layer 135a comprises one or more at least substantially reflective structures that are operable to at least substantially conduct electricity. Reflective conducting layer 135a, in this embodiment, comprises a layer of metal, such as aluminum, that is substantially reflective
30 of optical signals 162 incident thereon and substantially conductive of electricity. Reflective conducting layer

135a and inner conductive layer 133a may comprise single layers of one material, or may alternatively comprise multiple layers of one or more materials.

Reflective conducting layer 133a resides outwardly
5 from inner conductive layer 131a and/or 133a. Throughout this document, the term "inner conductive layer" is used to refer to material disposed inwardly from a moveable mirror layer, which is operable to at least substantially conduct electricity. Inner conductive layer 133a may
10 comprise, for example, semiconductor substrate 131a, which has been doped sufficiently to render it at least substantially conductive. In another embodiment, a layer 133a of metal or a layer of doped polysilicon can be formed outwardly from semiconductor substrate 131a, and
15 that layer 133a can comprise the "inner conductive layer." It is not necessary that the inner conductive layer comprise a continuous structure. Inner conductive layer 133 could, for example, comprise a series of adjacent electrically coupled strips (or other
20 discontinuous structures) of material.

MEMS device 130a is formed so that a space 137 resides between reflective conducting layer 135a and inner conductive layer 131a (or 133a if used). Various layers interstitial to layers 135 and substrate 131 may
25 be formed for various purposes. Regardless of any other structures formed, however, some amount of space 137 resides between reflective conducting layer 135 and substrate 131, to facilitate reflective conducting layer 135a moving inwardly toward substrate 131a.

30 MEMS device 130 receives optical signals 162 at a grazing angle THETA to reflective conducting layer 135a.

05746832 "122200

Reflecting conducting layer 135a reflects a substantial copy of signal 162 away from MEMS device 130a.

5 Movement of reflective conducting layer 135a toward substrate 131a is accomplished by establishing a voltage differential between reflective conducting layer 135a and substrate 131a or, if used, conductive layer 133a. This voltage differential creates an electrostatic force between the two at least substantially conductive layers, which tends to pull reflective conducting layer 135a
10 toward substrate 131a.

In the illustrated embodiment, reflective conducting layer 135a is biased with a voltage 136, while inner conductive layer 133a is coupled to ground 138. Other voltage biasing techniques may be used. For example,
15 voltage 136 may be applied to inner conductive layer 133a, and reflective conducting layer 135a may be grounded. As another example, a first voltage may be applied to reflective conducting layer 135a, while a second voltage, which is different from the first
20 voltage, is applied to inner conductive layer 133a. Any biasing scheme operable to establish a voltage differential between layers 135a and substrate 131a, or layer 135a and layer 133a (if used), is within the scope of the invention. Of course, semiconductor substrate
25 131a may itself comprise the "inner conductive layer."

FIGURE 3b is a block diagram of another embodiment of a moving mirror 130b useful, for example, in devices shown in FIGURE 2a-2d. Moving mirror device 130b also comprises a MEMS device. MEMS device 130b includes a
30 substrate 131b, and may also include a conductive layer 133b. Conductive layer 133b is similar in structure and

function to conductive layer 133a shown in FIGURE 3a. Substrate 131b is similar in structure and function to substrate 131a shown in FIGURE 3a.

MEMS device 130b also includes a plurality of
5 reflective conducting strips 135b. Reflective conducting strips may comprise any material operable to substantially reflect an incident optical signal 162 and to substantially conduct electricity. Reflective conducting strips 135b may comprise, for example, doped
10 polysilicon or a metal, such as aluminum. In addition, inner conductive layer 133b and/or reflective conductive strips 135b may comprise multiple layered structures.

Various structures may be formed interstitial to reflective conducting layer 135b and substrate 131b for
15 accomplishing various functions and results. Regardless of what structures are formed interstitial to layers 135b and substrate 131b, a space 137 is formed between reflective conducting strips 135b and substrate 131b to facilitate movement of reflecting conductive strips 135b
20 toward substrate 131b.

Movement of reflective conducting strips 135b toward substrate 131b is accomplished by establishing a voltage differential between strips 135b and substrate 131b (or conductive layer 133b, if used). As a particular
25 example, strips 135b may be coupled to ground 138, while substrate 131b (or conductive layer 133b) is coupled to a voltage source 136. Again, other methods of creating a voltage differential could be used. For example, strips 135b could be coupled to a voltage source, while
30 substrate 131b (or conductive layer 133b) are coupled to

a ground, or differential voltage sources could be coupled to each of these layers.

FIGURE 3c shows another view of MEMS device 130b. As shown in FIGURE 3, each end of each of strips 135b is anchored to, for example, substrate 131b. In this embodiment, all strips 135b are coupled to the same voltage potential. When a voltage differential is created between strips 135b and conductive layer 133b, all strips 135b move toward substrate 131b. The embodiment depicted in FIGURES 3b and 3c provides an advantage of controlling air damping during movement of strips 135b toward substrate 131b. In particular, air gaps 139 between strips 135b allow air in space 137 to escape when strips 135b move toward substrate 131b. Air gaps 139 can be optimally sized to provide adequate control of air damping, while minimizing loss associated with optical signals 162 impinging on strips 135b.

Although the illustrated embodiment shows strips 135b as being elongated rectangular strips, other shapes and configurations could be used without departing from the present invention. In addition, although the illustrated embodiment shows each of strips 135b as being substantially identical to other strips 135b, various of strips 135b could have different dimensions than others without departing from the present invention.

As a particular example of a biasing technique, moveable mirror devices 130a and/or 130b could be implemented in a configuration such as device 105 shown in FIGURE 2b. Device 105 could be biased to switch between a state where moveable mirror elements of mirrors 130 and 140 reside at positions 132 and 144,

respectively, to a state where those mirror elements switch to positions 134 and 142, respectively. This switching action would create a longer path length (DELTA $d/2$) for first signal copy 162 and a shorter path length
5 (DELTA $d/2$) for second signal copy 164, resulting in a total path difference of DELTA d .

Mirrors 130 and 140 could be biased to accomplish this switching, for example, by applying a control voltage to mirror 140 and no voltage to mirror 130 while
10 device 105 remains in the first state. This would cause mirror 140 to remain in position 144 and mirror 130 to remain in position 132. When switching is desired, device 105 can terminate the control voltage applied to mirror 140, causing the moveable mirror element to return
15 to position 142, and apply a control voltage to mirror 130, causing the moveable mirror element to be drawn to position 134. Other biasing techniques could be used consistent with the present invention.

20 II. Variable Attenuation

One particular aspect of the invention involves a novel variable attenuator and method for providing variable attenuation. FIGURE 4 shows a block diagram of one embodiment of a variable attenuator 200. Variable
25 attenuator 200 is described with reference to a configuration similar to that of apparatus 100 shown in FIGURE 1a. Attenuator 200 could alternatively be constructed using other configurations, such as those shown in FIGURES 1c-1d.

30 In this example, variable attenuator 200 includes a first beam splitter 220, which receives an input signal

260 and sends a first signal copy 262 toward a first mirror 230, and a second signal copy 264 toward a second mirror 240. First and second mirrors 230 and 240 reflect first and second signal copies 262 and 264 toward a
5 second beam splitter 250. Second beam splitter 250 combines components of the reflected first and second signal copies 262 and 264 to form output signal 272.

One or both of mirrors 230 and 240 can comprise a moveable mirror structure operable to vary its location
10 anywhere between position 232 and position 234 to result in a change in the length of the path of first and/or second signal copies 262 and 264 through attenuator 200. In operation, control signals 236 and /or 239 are selectively applied to moveable mirrors 230 and/or 240,
15 respectively, to cause one or more of those mirrors to move relative to first and/or second beam splitters 220 and 250. The further mirrors 230 and/or 240 are moved, the higher the degree of phase shift between first and second signal copies 262 and 264. The intensity of
20 output signal 272 is proportional to \cos^2 of one half of the phase difference PHI between first and second signal copies 262 and 264. Therefore, by controlling the amount of movement each mirror 230 and/or 240 experiences, the intensity or attenuation of output signal 272 can be
25 regulated.

Although variable attenuator 200 is shown as having only one mirror 230/240 in each arm of the device, additional mirrors could be implemented in each arm without departing from the scope of the invention. In
30 addition, although grazing angle THETA in FIGURE 4 is shown as approximately forty-five degrees, other grazing

002221 228460

angles could be implemented consistent with the invention.

III. Optical Switching

5 In another aspect of the invention, a novel digital switching architecture and methodology is presented. FIGURE 5a shows a block diagram of a one-by-two optical switch 300. In this example, optical switch 300 is similar in structure to variable attenuator 200, which
10 bears similarity to the configuration shown in FIGURE 1a. Optical switch 300 could, however, alternatively be constructed using other configurations, such as those shown in FIGURES 1c-1d.

In the illustrated embodiment, optical switch 300
15 includes a first beam splitter 320, which receives an input signal 360 and sends a first signal copy 362 toward a first mirror 330, and a second signal copy 364 toward a second mirror 340. First and second mirrors 330 and 340 reflect first and second signal copies 362 and 364 toward
20 a second beam splitter 350. Second beam splitter 350 combines components of the reflected first and second signal copies 362 and 364 to form output signals 372 and 374.

One or both of mirrors 330 and 340 can comprise a
25 moveable mirror structure operable to vary its position to result in a change in the length of the path of and phase difference between first and/or second signal copies 362 and 364. The intensity of first output signal 372 is proportional to \cos^2 of one half of the phase
30 difference PHI between first and second signal copies 362 and 364. The intensity of second output signal 374 is

002221 228460

proportional to \sin^2 of one half the phase difference PHI between first and second signal copies 362 and 364. Therefore, when there is no phase difference (or a phase difference of $2\text{-}\pi$, or an even multiple thereof), first
5 output 372 is at a maximum, while second output 374 is zero, or near zero. When the phase difference equals an odd multiple of π , second output 374 is at a maximum, while first output 372 is zero, or near zero. By varying the positions of mirrors 330 and/or 340 to switch between
10 a phase difference of, for example, approximately zero and π , optical switch 300 facilitates switching between first output 372 and second output 374.

FIGURE 5b is a block diagram showing one embodiment of a two-by-two switch 310. Two-by-two switch 310 is
15 similar in structure and function to one-by-two switch 300 described with respect to FIGURE 5a, except two-by-two switch 310 receives both a first input 360a (labeled "A1") and a second input 360b (labeled "A2") at beam splitter 320. Of course, optical switch 310 could also
20 be constructed using elements having other configurations, such as those depicted in FIGURES 1c-1d.

In this example, beam splitter 320 sends a copy of each input signal 360a and 360b toward first and second mirrors 330 and 340, which reflect those signal copies
25 toward beam splitter 350. Depending on the position of mirrors 330 and/or 340, switch 310 provides pass through or cross over operation to outputs 372 and 374.

For example, mirrors 330 and/or 340 could be positioned to provide no phase shift between the signal
30 copies of each arm, resulting in pass through operation where input 360a passes through to output 372 and input

002221 2284760

360b passes through to output 374. Alternatively, mirrors 330 and/or 340 could move to provide a phase shift resulting in cross-over operation, where input 360a crosses over to output 374 and input 360b crosses over to output 372. Of course, mirrors 330 and 340 could also be initially positioned to provide cross-over operation in a first state, and pass-through operation when one or more of the mirrors are moved.

FIGURE 5c is a block diagram showing another example of a two-by-two optical switch 400, and optionally added components to enable further switching stages. Elements represented in dashed lines comprise optional elements that can be added to provide additional switching stages. As previously discussed, although optical switch 400 uses a elements similar in configuration to those shown in FIGURE 1a, optical switch 400 could implement elements having alternative configurations, such as those shown in FIGURES 1c-1d.

In a basic two-by-two embodiment (ignoring the elements shown as coupled by dashed lines), switch 400 includes a first optical switch element 405, which receives a first optical signal 460a. Switch 400 further includes a second optical switch element 410, which receives a second optical signal 460b. Each of first and second optical switch elements 405 and 410 includes a first beam splitter 420, which receives input signals 460a and 460b, respectively, and sends a first signal copy 462 toward a first mirror 430, and a second signal copy 464 toward a second mirror 440. First and second mirrors 430 and 440 reflect first and second signal copies 462 and 464 toward a second beam splitters 450.

Second beam splitters 450 combine the reflected first and second signal copies 462 and 464 to form output signals 472a-b and 474a-b.

In the illustrated embodiment, output signals 472b
5 and 474a are communicated toward a beam combiner 456,
which combines those signals to create output signal 480.
Also in this embodiment, output signals 472a and 474b
reflect off of mirror 452 and 454, respectively, toward a
beam combiner 458, which combines those signals to create
10 output signal 490. Beam combiners 456 and 458 may
comprise any structure or combination of structures
operable to receive a plurality of signals and combine
those signals into one or more output signals. For
example, beam combiners 456 and 458 may each comprise a
15 50/50 beam splitter.

Some or all of mirrors 430a-b and 440a-b can
comprise moveable mirror structures operable to vary
their positions to result in changes in the length of the
path of and phase difference between first and/or second
20 signal copies 462 and 464. By varying the positions of
mirrors 430 and/or 440 to switch between a phase
difference of, for example, approximately zero and π ,
each of optical switches 400 facilitates switching
between first output 472 and second output 474.

25 Through appropriate combinations of mirror
movements, switch 400 can operate in either pass-through
or cross-over mode. For example, mirrors 430a and/or
440a can be operated to create no phase shift between
first and second signal copies 462a and 464a, while
30 mirrors 430b and 440b can be manipulated to create no
phase difference between first and second signal copies

262b and 264b. This operation would result in a pass-
though mode of operation, allowing signals 460a and 460b
to pass through to outputs 480 and 490, respectively. In
particular, in this mode of operation, a zero phase
5 difference between first and second signal copies 462b
and 464b results in output 474b being near zero, while
output 472b is near a maximum. An approximately Pi phase
difference between first signal copy 462a and second
signal copy 464a results in output 472a being near a
10 maximum, while output 474a is near zero. Output 480,
which is a combination of outputs 472b (maximum) and 474a
(zero), therefore, equals output 472b, which corresponds
to signal 460b. Output 490, which is a combination of
outputs 472a (maximum) and 474b (zero), therefore, equals
15 output 472a, which corresponds to input signal 460a.

As another example, mirrors 430a and/or 440a can be
manipulated to create approximately a Pi phase difference
between first and second signal copies 462a and 464a,
while mirrors 430b and 440b can be operated to create an
20 approximately Pi phase difference between first and
second signal copies 262b and 264b. This operation would
result in a cross-over mode of operation, causing signal
460a to cross over to output 480, while signal 460b
crosses over to output 490.

25 Although Figure 5c is a block diagram showing one
embodiment of a two-by-two switch, additional switching
elements could be combined in a similar manner to create
an n-by-n optical switch. For example, by implementing
components shown in dashed lines in FIGURE 5c and
30 substituting 2x2 switches for beam combiners 456 and 458,
switch 400 becomes a four-by-four switch. In that

5

10

15

20

30

splitter 120 communicates copies of input signal 160 toward a first mirror and a second mirror at step 515. This may include, for example, a partially silvered mirror receiving input signal 160 and communicating a first signal copy 162 toward first movable mirror 130, and a second signal copy 164 toward second movable mirror 140. First and second mirrors 130 and 140 receive signal copies 162 and 164 at grazing angles other than 90 degrees. In a particular embodiment, mirrors 130 and 140 may receive signal copies 162 and 164 at grazing angles less than 45 degrees. This configuration provides an advantage of minimizing displacement of mirrors 130 and/or 140 to achieve a given signal path difference.

One or more mirrors 130 and/or 140 comprises a MEMS device having a moveable mirror layer that changes its position in a substantially piston-like motion at step 520 to result in a difference in phase between signal copies 162 and 164. This may include, for example, first mirror layer 130 switching from position 132 to position 134, and/or mirror layer 140 switching from position 144 to position 142. First and second mirrors 130 and 140 reflect signal copies 162 and 164, respectively, toward an output at step 525. This may include, for example, first and second mirrors 130 and 140 reflecting signal copies 162 and 164 toward a second beam splitter 150. Alternatively, first and second mirrors 130 and 140 may reflect signal copies to additional moveable mirror elements (see, e.g. FIGURE 2c). Implementing additional moving mirrors in each arm of device 105 provides an advantage of minimizing the displacement of any one of

the movable mirrors while attaining a given signal path difference.

Phase shifted components of first and second signal copies 162 and 164 are combined at step 530 to produce one or more output signals 172 and/or 174. Depending on the level of displacement of mirrors 130 and/or 140, device 105 can operate to provide, for example, phase shifting, variable attenuation, and/or switching functionality on input signal 160.

IV. Polarization Controllers

FIGURE 7a is a block diagram showing an exemplary embodiment of a polarization controller 610. In this particular embodiment, polarization controller 610 comprises a phase shift-based polarization controller. Rather than requiring physical rotation of the polarization controller, polarization controller 610 uses phase shifts between the principal modes of input signal 616 to orient the output states of polarization.

In the particular example shown in FIGURE 7a, polarization controller 610 includes three stages of phase shifters 620, 622, and 624, each operable assist in translating the input state of polarization to a desired output state of polarization. In this embodiment, first phase shifter 620 couples to a polarization beam splitter 618, which receives input optical signal 616 and separates the two principal modes of polarization. Each of phase shifters 620-624 introduces a phase shift between these two principal modes of polarization.

Each phase shifter 620-624 comprises a device or collection of devices operable to introduce a phase shift

into an optical signal it receives. Phase shifters 620-624 may comprise, for example, micro-electro-mechanical systems (MEMS) comprising moveable mirror elements in each arm facilitating a phase shift between signal copies communicated through each arm. Any device operable to introduce a phase shift into an optical signal, however, may be used.

In this example, beam splitters 626 and 628 couple second phase shifter 622 to first phase shifter 620 and third phase shifter 624, respectively. In one embodiment, at least two phase shift stages share a common beam splitter. The example shown in FIGURE 7a depicts phase shifters 620-624 sharing two common beam splitters 626 and 628. In another embodiment, phase shifters 620-624 could, for example, all share one common beam splitter.

In any case, each of beam splitters 626-628 may comprise, for example, a partially silvered mirror, a mirror having one or more layers of a dielectric coating, or a fiber coupler. In a particular embodiment, each of beam splitters 620-624 comprises an approximately 50/50 beam splitter. While other beam splitter ratios can be used consistent with the scope of the invention, an approximately 50/50 beam splitter maintains the symmetry of the device to provide a good contrast ratio.

In one particular embodiment, beam splitters 626 and 628 may each comprise a mode coupling beam splitter. For example, beam splitters 626 and 628 may include or be coupled to a polarization converter to render beam splitters 626 and 628 mode coupling. This embodiment ensures that polarization controller 610 can convert any

arbitrary state of polarization (including eigen modes)
into any other state of polarization. In addition, this
embodiment produces a single output from polarization
beam splitter 619, which reduces polarization dependent
5 losses that might otherwise be associated with systems
having multiple outputs.

The embodiment of polarization controller 610 shown
in FIGURE 7a also includes a polarization beam splitter
619, which receives a phase shifted signal from third
10 phase shifter 624, and aligns the two principal modes of
polarization of that signal as desired.

The embodiment shown in FIGURE 7a provides
significant advantages over other polarization controller
designs, by facilitating reorientation of the principal
15 modes of polarization without requiring the use of
physical rotation of the compensator, physical squeezing
of the fiber communication line, the use of expensive
lithium niobate waveguide devices, or the use of
additional beam splitter elements due to the presence of
20 bulk wave plates between stages of phase shifters.

FIGURE 7b is a block diagram of one particular
configuration of a polarization controller 610a.
Polarization controller 610a as shown in FIGURE 7b
includes a plurality of phase shifter stages 620-624 each
25 comprising a MEMS-based device, such as the device
described above with respect to FIGURE 4. Although each
of phase shifter stages 620-640 has a similar
configuration to apparatus 100 shown in FIGURE 2a, phase
shifter stages 620-640 could implement other
30 configurations, such as those shown in FIGURES 1c-1d.

In the illustrated example, each phase shifter 620-624 includes two arms 662 and 664, at least one of which comprises a moveable mirror structure 630 and/or 640. Mirrors 630 and/or 640 are operable to move in response to one or more control signals to result in a change in the length of the signal path and, therefore, a phase shift between signal copies communicated through the arms of phase shifters 620-624. Phase shifter stages 620-624 are coupled together by beam splitters 626 and 628. In this example, phase shifter stages 620 and 622 share beam splitter 626, while phase shifter stages 622 and 624 share beam splitter 628.

In this example, polarization beam splitter 618 receives optical input signal 616 and separates the two principal modes of polarization onto a first signal path 662 and a second signal path 664. A polarization beam splitter 619 receives phase shifted signals from third phase shifter stage 624 and aligns the principal modes of polarization with the principal axes of delay line 612.

The heretofore described embodiment of polarization controller 610a succeeds in transforming any input states of polarization that are not eigen modes of the system. For example, s-polarized and p-polarized waves are not transformed into any other state using that configuration. To facilitate transforming any arbitrary state of polarization (including eigen modes) into any other state of polarization, FIGURE 7b also shows the optional use of polarization converter 635 to the first phase shift stage (630a/640a) of polarization controller 610a.

As a particular example, assume that polarization beam splitter 618 operates to reflect the s-polarized waves and to transmit the p-polarized waves. Polarization converter 635 receives the p-polarized waves and converts them to s-polarized waves, so that beam splitter 628 can combine s-polarized waves coming from first and second arms 662 and 664 and communicate the combined signals toward the second phase shift stage. Although this example shows polarization converter 635 coupled between MEMS device 640a and beam splitter 626, polarization converter 635 could alternatively reside between polarization beam splitter 618 and MEMS device 640a. In addition, polarization converter 635 could alternatively reside in first arm 662 of polarization controller 610a.

The polarization controller of FIGURE 7b also shows the optional use of a polarization converter 637 coupled to the last phase shift stage (630c/640c). Polarization converter 637 operates to convert the polarization of the received signal to match that of the signal in the opposing arm of the phase shift stage, so that polarization beam splitter 619 will concentrate the output into one output signal. Polarization converter 637, can reduce or eliminate polarization dependent losses otherwise associated with the output signal. Although this example shows polarization converter 637 coupled between MEMS device 640c and beam splitter 619, polarization converter 635 could alternatively reside between polarization beam splitter 619 and MEMS device 640c. In addition, polarization converter 637 could

Polarization converters 635 and 637 may comprise any device or combination of devices operable to flip the polarization of an incoming signal to an orthogonal mode of polarization. Wave plates, Transverse Electrical Transverse Magnetic (TETM) converters, Faraday converters, and mirrors positioned so as to flip the polarization of an incoming signal to a polarization orthogonal to the input state of polarization provide just a few examples of polarization converts suitable for use with this system.

Although FIGURE 7b shows the optional use of a single polarization converter in the first and last phase shift stages, alternatively, a polarization converter could reside in each arm of the first and/or last phase shift stages. In this manner, the physical symmetry of the device can be maintained, so as to increase the contrast ratio of the device. As one particular non-limiting example, where polarization converters are used in each arm of the first and/or last phase shift stage, each polarization converter can comprise a half wave plate -- one oriented at forty-five degrees to the mode axis, the other oriented parallel to the mode axis. Multiple polarization converters in a single phase shift stage may, but need not, be formed from like materials.

FIGURE 7c shows an alternate embodiment of a polarization controller 610b operable to transform any linear input state of polarization to any arbitrary output state of polarization. In this example, polarization controller 610b includes a polarization beam

5

10

20

25

30

control signal, changes its position to create a further phase difference between the signal copies received from beam splitter 668. Reflective surfaces 680 and 690 reflect the further phase shifted signal copies toward beam splitter 668, which receives the signal copies and combines components of those signals.

Beam splitter 668 then communicates the combined components toward reflective surfaces 660 and 670, which introduce yet a further phase shift between the principal modes, and communicate the further phase shifted modes toward polarization beam splitter 658. Polarization beam splitter 658 communicates a phase shifted output 673 toward a circulator 675, which directs the phase shifted output signal from polarization controller 610b.

As with polarization controller 610a, polarization controller 610b may optionally include a polarization converter 636. Polarization converter 636 operates to facilitate polarization control of eigen modes and operates to reduce polarization dependent losses.

Polarization controller 610b includes three stages of phase shift. Reflective surfaces 660 and 670 comprise the first and third phase shift stages, while reflective surfaces 680 and 690 comprise the second phase shift stage. In this example, all phase shift stages share a single beam splitter 668. By sharing one beam splitter between multiple phase shift stages, this embodiment of the invention advantageously reduces the number of components required to provide polarization control. For example, this embodiment reduces the number of beam splitters needed, and also reduces the number of polarization converters necessary to both process eigen

09746823 13300
002224 2284260

modes and reduce or eliminate polarization dependent losses. In addition, this embodiment facilitates implementing a single polarization beam splitting device to serve as both the first (input) polarization beam splitter and the second (output) polarization beam splitter.

Polarization controllers 610a and 610b can be used in a variety of signal processing applications. For example, use in conjunction with polarization sensitive optical components, use in polarization multiplexed lightwave transmission systems, use in coherent communication systems, and use in polarization mode dispersion compensators are just a few examples of applications for polarization controllers 610a and 610b.

If the characteristic for which the polarization controller is being used changes at a rate that is slower than the reset speed of the polarization controller and, ideally, if the polarization controller can switch at a rate faster than the bit rate of the information being processed, the polarization controller can be made infinitely rotatable (also known as "reset free" or "endless polarization rotation"). In other words, the polarization controller can be used to provide one phase adjustment along the Poincare Sphere, reset, and provide a second phase adjustment modulo 2π from the first phase adjustment. In this manner, phase shifters 620-624 can emulate a single large phase shift using numerous smaller phase shifts between changes in polarization. Through this technique, polarization controller 610a can simulate an ability to provide a number of rotations on the Poincare Sphere, without actually having the physical

range that would otherwise be necessary to perform the transformation.

One example of a device that is capable of switching at speeds faster than most signals' polarization changes is a MEMS-based phase shifter stage - in particular those operable to undergo substantially piston-like motion and using multiple moving mirror strips to control air damping. For example, in mitigating polarization mode dispersion, polarization controller 610a can switch at speeds faster than once each milli-second, the approximate time scale on which polarization mode dispersion varies. Therefore, MEMS-based phase shifter stages 620-624 capable of switching at speeds significantly greater than, for example, once each milli-second can be implemented to provide an endlessly rotatable polarization controller in a PMD compensator

FIGURE 7C is a graph showing realized switching speeds using one particular embodiment of polarization controller 610, which implements MEMS based phase shift stages similar to the device depicted in FIGURE 3a. In this example, trace 152 shows a switching of the phase shift stages in response to a control voltage 150. As shown in this example, rise times of seven hundred microseconds have been obtained. Other switching speeds may be ascertainable, depending on the processing demands and particular device characteristics utilized. For example, faster switching speeds can be obtained using an embodiment similar to that shown in FIGURE 3b.

Another technique for producing an infinitely rotatable polarization controller is to implement at least four stages of phase shifters. For example,

although the embodiments shown in FIGURES 7b and 7c include three stages of phase shifters, one or more additional phase shift stages could be cascaded with the illustrated stages to render the controllers endlessly rotatable based on the number of phase shift stages being used. Using four or more stages of phase shifters, for example, allows for resetting one stage of phase shifters, while one or more other stages is processing the signal. This facilitates endless polarization rotation while maintaining lower switching speeds.

FIGURES 8-13 provide various examples of methods and apparatus employing polarization controllers of the present invention. For ease of description, FIGURES 8-13 illustrate various examples using details of polarization controller 610a shown in FIGURE 7b. It should be noted that other embodiments, such as polarization controller 610b shown in FIGURE 7c (or various derivatives thereof) could also be used in the examples given in FIGURES 8-13 without departing from the scope of the invention.

One aspect of the invention provides novel methods and apparatus useful in mitigating polarization mode dispersion (PMD). FIGURES 8a-8h are block diagrams showing various embodiments of systems implementing PMD compensators, PMD compensator designs, and components suitable for use in PMD compensators. FIGURE 8a is a block diagram of an optical communication system implementing a PMD compensator along with one or more margin enhancing elements. As optical communication systems communicate information at higher and higher rates, the need for mitigating polarization mode dispersion increases. In addition, as the bit rate

increases, so does the need for more system margin. Conventional systems operating at, for example, ten Giga-bits per second have implemented margin enhancing techniques, such as distributed Raman amplification, forward-error-correction, and dispersion management. To date, however, no system has emerged which optimizes the location and/or operation of one or more of these margin enhancement techniques in conjunction with mitigation of polarization mode dispersion.

10 In one aspect of the invention, an optical communication system is presented that optimizes the use of PMD compensators in conjunction with one or more margin enhancing devices. System 550 shown in FIGURE 8a shows an example of one such system. System 550 includes
15 a plurality of fiber spans 551a-551n coupled between an optical source 552 and an optical receiver 568. In-line amplifiers 558a-558n reside between fiber spans 551 to provide amplification of the optical signals traversing those spans. These amplifiers may comprise, for example,
20 erbium doped amplifiers, Raman amplifiers, or any other suitable optical amplifying device.

System 564 also includes a PMD compensator 564 operable to reduce polarization mode dispersion in the optical signals being communicated. In this embodiment,
25 PMD compensator 564 resides somewhere along the fiber span coupling the last in-line filter 558n and receiver 568. System 550 also includes one or more pre-amplifiers 554 coupled to or integral with optical source 552, and one or more post-amplifiers 566 coupled to or integral
30 with optical receiver 568. One or more post-amplifiers

Coupling PMD compensator 564 at or near the final fiber span provides an advantage of optimizing the optical signal to noise ratio. Placing PMD compensator close to the end of the transmission system results in attenuating both the signal and the noise equally, allowing the system to maintain a good signal-to-noise ratio.

20 This example also implements distributed Raman
amplification to enhance the system margin. In
particular, system 550 implements counter-propagating
pumps 560a-560n, which help prevent coupling of pump
fluctuations to the optical signals being communicated by
25 system 550. Also in this example, system 550 utilizes
forward-error-correction circuitry 570 at or accessible
to receiver 568.

Although this particular example shows the use of three margin enhancing techniques, the invention does not require each of these techniques. Rather, by implementing a polarization mode dispersion compensator

and at least one margin enhancing technique, this aspect of the invention provides significant advantages in facilitating optical signal transmission at speeds of, for example, forty Giga-bits per second or more. In addition, by locating the PMD compensator near the optical receiver, system 550 maintains a good signal-to-noise ratio.

FIGURE 8b is a block diagram showing one embodiment of a PMD compensator 600 including a polarization controller (PC) coupled to a delay element controlled through control circuitry 614. In a particular embodiment, polarization controller 610 may be similar in structure and function to polarization controller 610 shown in FIGURE 7a. PMD compensator 600 operates to reestablish a linear polarization between the various modes of an incoming optical signal 616, by delaying the mode associated with the faster axis of the fiber to result in an equalization in communication speeds of both principal axes.

In operation, PMD compensator 600 receives an optical signal 616 at polarization controller 610. In one embodiment, polarization controller 610 is operable to receive an optical signal having any arbitrary state of polarization and to convert the signal to one having a linear state of polarization. In another embodiment, polarization controller 610 operates to receive an optical signal having any arbitrary state of polarization and to convert that signal to one having any other state of polarization. Polarization controller 610 adjusts the state of polarization of each of the principal modes of input signal 616, and passes the adjusted signal to a

delay element 612, which delays the leading mode and/or speeds up the lagging mode of polarization. The output from delay element 612, or an electrical version thereof, is then fed back to control block 614, which generates
5 control signals for use by polarization controller 610 in continually adjusting the state of polarization of each principal mode.

FIGURE 8c is a block diagram showing one possible embodiment of a polarization controller 610 coupled to a
10 delay element 612. In this particular embodiment, polarization controller 610 comprises a phase shift-based polarization controller comprising at least three stages of phase shifters 620, 622, and 624, each operable to provide one degree of freedom in translating the input
15 state of polarization to a desired output state of polarization. In this embodiment, first phase shifter 620 couples to a polarization beam splitter 618, which receives input optical signal 616 and separates the two principal modes of polarization. Phase shifters 620-624
20 introduce phase shifts between these two principal modes of polarization. In the illustrated embodiment, beam splitters 626 and 628 couple second phase shifter 622 to first phase shifter 620 and third phase shifter 624, respectively. In this example, each of phase shifters
25 620-624 shares a common beam splitter 626 or 628. Phase shifters 620-624 may comprise, for example, micro-electro-mechanical systems (MEMS) comprising moveable mirror elements in each arm facilitating a phase shift between signal copies communicated through each arm of
30 the phase shifter, as shown in FIGURES 7b and 7c. Sharing beam splitters between phase shifter stages

Delay element 612 can comprise any device -- hardware, software, firmware, or combination thereof operable to provide a delay to one component of an optical signal with respect to another component of that signal. In a particular embodiment, delay element may comprise, for example, a length of polarization maintaining fiber (PMF) that has been intentionally formed so that one of its principal axes is faster than the other. Where delay element 612 comprises a fixed delay element, polarization controller 610 should comprise at least three stages of phase shifters 620-624

to ensure adequate flexibility in aligning the principal modes of polarization of input signal 616 to the fast and slow axes of fixed delay element 612. Polarization controller 610 could alternatively, however, comprise additional phase shift stages beyond the three shown in FIGURE 7b. Where PMD compensator 600 comprises a fixed delay element 612, polarization controller 610 can comprise any number of phase shift stages greater than two. Additional stages of phase shifters provide an advantage of allowing the use of more simple control algorithms in control block 614.

Other typed of delay elements could be used consistent with the invention. For example, delay element 612 could comprise one or more retardation plates, or other suitable birefringent material. In another embodiment, delay element 612 could comprise a variable delay line comprising, for example, a polarization controller coupled between lengths of polarization maintaining fiber. In still another embodiment, delay element 612 could comprise an electronic delay circuit. Chirped HiBi fiber gratings provide still another example of a delay element applicable to the present invention. For ease of description, the following examples will assume use of polarization maintaining fiber as a delay element. Other delay elements could be used consistent with the invention.

The embodiment shown in FIGURE 8c provides significant advantages over other PMD compensator designs, by mitigating the effects of polarization mode dispersion without requiring the use of physical rotation

of the compensator, physical squeezing of the fiber communication line, the use of expensive lithium niobate waveguide devices, or the use of bulk wave plates between each stage of phase shifters. Moreover, while this
5 embodiment can be used with a variable delay line, it does not require the use of more expensive variable delay elements. Instead, it facilitates the use of an inexpensive fixed delay element, such as a length of polarization maintaining fiber.

10 Where polarization controller 610 implements a polarization converter coupled to the last phase shift stage, the polarization controller generates a single output. In that case, a delay element can be coupled directly to the output of the polarization controller.
15 FIGURES 8d-8e are block diagrams showing illustrative examples of coupling delay elements 612a and 612b, respectively, to a polarization controller that does not use a polarization converter to result in a single output. In FIGURE 8d, delay element 612a comprises a
20 fixed delay element including a polarization beam splitter 613 coupled to a length of polarization maintaining fiber 615. In this example, mirrors 607 and 609 reflect the two phase shifted outputs of polarization beam splitter 619 toward polarization beam splitter 613.
25 Polarization beam splitter 613 acts as a signal combiner to form output 617, which is communicated to polarization maintaining fiber 615.

Delay element 612b shown in FIGURE 8e includes a first delay line 621 and a second delay line 623, each
30 coupled to polarization beam splitter 619. In this particular example, each of delay lines 612 and 623

09746822 122000

comprises a length of polarization maintaining fiber. In the illustrated embodiment, polarization beam splitter 619 directs a first phase shifted principal mode of polarization toward first delay line 621, and directs a
5 second phase shifted principal mode of polarization toward a mirror 631, which reflects the second principal mode toward second delay line 623. A mirror 633 receives a delayed phase shifted principal mode from second delay line 623, and directs that signal toward a polarization
10 beam splitter 625. Polarization beam splitter 625 receives the delayed phase shifted principal modes of polarization from delay lines 621 and 623, and combines those signals into a compensated output 627.

The embodiments of delay elements 612a and 612b
15 shown in FIGURES 8d and 8e are intended for illustrative purposes only. Other delay elements and/or configurations of elements could be used without departing from the scope of the invention.

A related aspect of the invention comprises a method
20 and apparatus for facilitating variable delay for use, for example, in a PMD compensator. FIGURE 8f is a block diagram of one embodiment of a variable delay line 700. Variable delay line 700 comprises at least one polarization controller 710 coupled between a pair of
25 polarization maintaining fibers (PMF) 712a-712b. Polarization maintaining fibers 712 are similar in structure and function to fixed delay element 612 described with respect to FIGURE 8b. Polarization controller 710 is similar in structure and function to
30 polarization controller 610 described with respect to FIGURES 7a and 8a.

09746622 122000

09746822 122000

In operation, first polarization maintaining fiber 712 receives an optical signal 705 having its two principal modes of polarization oriented for transmission substantially parallel with the principal axes of first polarization maintaining fiber 712a. First polarization maintaining fiber 712a communicates the lagging mode of polarization of signal 705 parallel to its faster axis, and communicates the leading mode of polarization of signal 705 parallel to its slower axis to generate a partially compensated signal 706.

Polarization controller 710 receives partially compensated signal 708 and performs a phase shift on that signal to align the principal modes with the principal axes of second polarization maintaining fiber 712b. Second polarization maintaining fiber 712b then communicates the leading mode of polarization of signal 708 on its slower principal axis, and communicates the lagging mode of polarization of signal 708 on its slower principal axis. In this example, a polarization beam splitter 713b receives the phase shifted signal from polarization beam splitter 719 of polarization controller 710, and facilitates transmission of the leading principal mode parallel to the slow axis and the lagging principal mode parallel to the fast axis of polarization maintaining fiber 712b.

By implementing multiple stages of polarization maintaining fiber coupled to a polarization controller, variable delay line 700 facilitates more granular control over compensation than a fixed delay element. To add still more granularity of control, additional stages of

FIGURE 8g is a block diagram showing one embodiment of a PMD compensator 750 implementing variable delay line 700. PMD compensator 750 includes a polarization controller 760 coupled to variable delay line 700 and a control block 714. Polarization controller 760 comprises a first polarization beam splitter 762 operable to receive optical signal 716 and to separate the principal modes of polarization of that signal, and a beam splitter 764 operable to align the principal modes of polarization of the phase shifted signal with the principal axes of variable delay line 780. In the illustrated embodiment, polarization controller 760 includes just two phase shifters 770 and 772 separated by a beam splitter 766. In a particular embodiment, beam splitter 766 may comprise an approximately 50/50 beam splitter. Implementing a variable delay line, such as variable delay line 700, allows PMD compensator to utilize a two stage phase-shift based polarization controller 760. While additional stages of phase shifters in polarization controller 760 could be used without departing from the scope of the invention, using variable delay line 700 facilitates similar PMD compensation to a three or more stage phase shift polarization controller, while eliminating a stage of phase shifters.

FIGURE 8h is a block diagram showing one possible embodiment of a two-stage phase shift based polarization controller 755 coupled to a variable delay element 780. In this example, each phase shifter stage 770-772 of polarization controller 755 comprises a MEMS-based

device, such as the device described above with respect to FIGURE 4. Although phase shifter stages 770-772 have a similar configurations to apparatus 100 shown in FIGURE 2a, phase shifter stages 770-772 could implement other configurations, such as those shown in FIGURES 1c-1d.

In this example, each phase shifter 770-772 includes two arms, at least one of which comprises a moveable mirror structure 730 and/or 740. Mirrors 730 and/or 740 are operable to move in response to one or more control signals to result in a change in the length of the signal path and, therefore, a phase shift between signal copies communicated through the arms of phase shifters 770-772. Phase shifter stages 720 and 722 share a beam splitter 766 coupled between those stages.

Polarization beam splitter 762 receives optical input signal 716 and separates the two principal modes of polarization onto a first signal path directed toward mirror 730a, and a second signal path directed toward mirror 740a. Each phase shift stage 770 and 772 introduces a phase shift between the principal modes of polarization of signal 716. A beam splitter 764 receives phase shifted signals from second phase shifter stage 772 and aligns the principal modes of polarization with the principal axes of variable delay line 780. Variable delay line 780 may comprise any device or combination of devices operable to provide a tunable delay line.

Using the configuration shown in FIGURE 8h, two stage polarization controller 755 can receive an input signal having any arbitrary state of polarization, and can generate an output signal having a linear state of polarization. Variable delay line 780 can then complete

FIGURE 9 is a flowchart showing one example of a method 900 of controlling the polarization of a signal and ultimately mitigating polarization mode dispersion. Method 900 begins at step 902 where polarization controller 610 receives optical signal 616 at step 902. Polarization controller 610 separates optical signal 616 into a leading principal mode of polarization and a lagging principal mode of polarization at step 904. This may include, for example, polarization beam splitter 618 receiving optical signal 616, and communicating first mode 662 toward first mirror 630 and communicating second mode 664 toward second mirror 640.

First beam splitter 626 communicates substantial
30 copies of phase shifted modes toward first and second
mirrors 630b and 640b, where a second phase shift is

introduced at step 912. First and second mirror 630b and 640b communicate the twice phase shifted modes 662 and 664 to second beam splitter 628 at step 914. Second beam splitter 628 receives the twice phase shifted modes and communicates copies of those signals to first and second mirrors 630c and 640c, where a third phase shift is introduced at step 918. In a particular embodiment, second beam splitter 628 may comprise a mode coupling beam splitter operable to flip the polarization of one of the modes, to facilitate communication of a single output signal and reduce polarization dependent losses.

Polarization beam splitter 619 receives phase shifted principal modes of polarization 662 and 664 and separates the principal modes of polarization at step 922. Steps 902 through 922 have described one example of a method of controlling polarization in an optical signal. This method may find application, for example, in a PMD compensator as discussed below, or in a polarization multiplexed lightwave transmission system, in a coherent communication system, or in conjunction with polarization sensitive optical components.

One particular method of mitigating polarization mode dispersion continues at step 924 where polarization controller 610 communicates the phase shifted principal modes of polarization to delay element 612. Although delay element 612 may comprise any of a variety of devices operable to introduce delay, in a particular embodiment, polarization controller 610 aligns the leading mode of polarization with a slow axis of a polarization maintaining fiber 612a at step 926, and aligns the lagging mode of polarization parallel to a

FIGURES 10a-10b are block diagrams showing various embodiments of a system and components thereof operable to mitigate polarization mode dispersion in multiple-wavelength optical signals. Where optical signals comprise multiple wavelengths, each wavelength will rotate in polarization differently as it traverses the optical fiber. Consequently, compensating for polarization mode dispersion must be done on a wavelength-by-wavelength basis. Conventional solutions to PMD compensation that offer endlessly rotatable operation - such as those using lithium niobate based polarization controllers - are very expensive, even on a single wavelength application. As optical systems implement more and more communication channels (using more and more wavelengths), the cost of PMD compensation using conventional equipment quickly becomes prohibitive.

One aspect of the invention provides an architecture that is easily and inexpensively replicated to facilitate arrays of PMD compensators capable of processing any number of wavelengths of light. System 800 as shown in FIGURE 10a includes an array of polarization controllers 810. Each polarization controller in array 810 comprises a MEMS-based phase shift polarization controller. System 800 also includes a delay element 812. Delay element 812 may comprise a fixed delay element, such as polarization

maintaining fiber 612 shown in FIGURE 8d, or a variable delay element, such as variable delay line 710 shown in FIGURE 8f. In the illustrated embodiment, all polarization controllers share a single delay element
5 812. Alternatively, system 10 could implement multiple delay elements 812, each servicing one or more polarization controllers of array 810.

Where delay element 612 comprises a fixed delay element, each polarization controller of array 810
10 comprises three or more stages of phase shifters, such as in polarization controller 610 shown in FIGURE 8d. Where delay element 612 comprises a variable delay element such as variable delay line 710 shown in FIGURE 8f, each polarization controller of array 810 may comprise as few
15 as two stages of phase shifters, as in polarization controller 760 shown in FIGURE 8g.

In the illustrated embodiment, system 800 further includes a wavelength division demultiplexer 807 coupled to the output of delay element 812, and an array of
20 detectors 823. Wavelength division multiplexer 807 is operable to receive a compensated signal 817 from delay element 812, separate the various wavelengths of that signal, and pass those wavelengths to a detector 823. Detectors 823 convert the optical signals received into
25 electrical signals for processing in an array of control circuitry 814. Control circuitry 814 generates control signals 821a-821n, which are communicated to associated polarization controllers of array 810.

In an alternative embodiment, demultiplexer 807 and
30 array of detectors 823 could be replaced by a variable filter or a scanning filter operable to sequentially

097445823 122200

filter each wavelength from signal 817, and to pass each wavelength to control array 814. Control array 814 could, for example, communicate control signals to array of polarization controllers 810 and also communicate a
5 signal to the scanning filter instructing the filter to deliver the next wavelength.

In operation, wavelength division demultiplexer 802 receives an optical input signal 816 having a plurality of wavelengths, and separates signal 816 into a plurality
10 of individual wavelength signals 806a-806n. In one embodiment, polarization controllers of array 810 each receive one of wavelengths 806a-806n for processing. Alternatively, system 800 may communicate only some of wavelengths 806 to polarization controller array 810, and
15 allow other wavelengths 806 to bypass polarization controller array 810 through bypass path 823. This may be useful, for example, where system 10 provides PMD compensation for communication systems using only some of the wavelengths of signal 816. In those cases, system 10
20 can provide efficiencies of compensating only those wavelengths being utilized, allowing non-utilized wavelengths to pass without processing.

Polarization controllers of array 810 receiving utilized wavelengths introduce phase shift into those
25 signals to align the principal modes of polarization to the appropriate axes of delay element 812. Wave division multiplexer 804 receives phase shifted signals 808a-808n from polarization controller array 810, multiplexes those signals into a one or more phase shifted optical signals
30 for communication to delay element 812. Delay element 812 communicates the leading mode of polarization

parallel to its faster axis, and communicates the lagging mode of polarization parallel to its slower axis to mitigate polarization mode dispersion.

Control array 814 receives compensated signals 817
5 and generates control signals 821 for feedback to polarization controllers of array 810. In a particular embodiment, control array 814 comprises an array of electronic circuitry, which receives electronic signals from one or more detectors 823 operable to convert
10 optical signals to electrical signals. Control signals 821 may comprise, for example, voltage signals operable to control the amount of movement in moveable mirror structures, such as 630 and 640 shown in FIGURE 7b or mirrors 730 and 740 shown in FIGURE 8h. Controlling the
15 amount of displacement of these mirrors controls the change in path length of signals communicating with those mirrors and, therefore, the phase shift of the resulting signals. This embodiment provides an advantage of facilitating use of readily available electronic control
20 circuitry for system 800.

FIGURE 10b is a block diagram showing one possible embodiment of polarization controller array 810. Polarization controller array 810 may be useful, for example, in a multiple-wavelength PMD compensator.
25 Alternatively, polarization controller array 810 could be applied to any system where it is desirable to control the polarization of multiple wavelengths in one or more optical signals. Although each polarization controller of array 810 is depicted as similar to polarization
30 controller 610a of FIGURE 7a, polarization controllers 810a-810n could alternatively comprise polarization

0022227 2289460

controllers, such as controller 610b shown in FIGURE 7c (or derivatives thereof).

In this example, each polarization controller 810a-810n of array 810 includes a polarization controller
5 similar to that shown in FIGURE 7b. Each phase shifter stage 820a-n through 824a-n (referred to generally as phase shifter stages 820-824) comprises a MEMS-based device, such as the device described above with respect to FIGURE 4. Each phase shifter stage 820-824 includes
10 two arms, at least one of which comprises a moveable mirror structure 630 and/or 640. Mirrors 630 and/or 640 are operable to move in response to one or more control signals 821 to result in a change in the length of the signal path and, therefore, a phase shift between signal
15 copies communicated through the arms of phase shifters 820-824. Phase shifter stages 820-824 are coupled together by beam splitters 826 and 828. Beam splitters 826-828 may comprise, for example, approximately 50/50 beam splitters. In this example, polarization beam
20 splitter 818 receives various wavelengths 806a-806n of optical input signal 816 and separates the two principal modes of polarization in those signals onto a first signal path and a second signal path. A polarization beam splitter 819 receives phase shifted signals from
25 third phase shifter stages 824 and aligns the principal modes of polarization with the principal axes of delay element 812.

Although the illustrated embodiment shows three stages of phase shifters, additional stages could be
30 implemented consistent with the present invention. Moreover, where delay element 812 comprises a variable

05746822 122000

5

10

20

30

Each polarization controller of array 810 separates its associated wavelength 806 into a first and a second principal mode of polarization at step 950. This may include, for example, polarization beam splitter 818 receiving one or more wavelengths 806 and separating those wavelengths into their principal modes of polarization. Each polarization controller of array 810 next introduces phase shift between the first and second modes of polarization of each wavelength at step 955. This may include, for example, introducing at least three stages of phase shift between the first and second modes of polarization to align each of the first and second modes with a principal axis of a fixed delay element. Alternatively, this may include introducing at least two stages of phase shift between the first and second modes of polarization to align each of the first and second modes with a principal axis of a variable delay line. In addition, polarization converters 635 and 637 could operate to flip polarizations of one of the signal copies, to facilitate processing of, for example, eigen modes, and to reduce polarization dependent losses.

25 Polarization controllers of array 810 communicate
phase shifted principal modes of polarization for
transmission through delay element 812 at step 960. This
may include, for example, multiplexing the plurality of
wavelength signals 806 into a single optical signal fed
30 to a common delay element 812. Alternatively, this may

Communicating principal modes of polarization
through delay element 812 may further comprise

Although array 810 of polarization controllers has been described as being useful in mitigating polarization mode dispersion, a similar array could be equally applicable to other situations in which it is useful to control polarization of multiple wavelength signals. For example, array 810 is equally suitable for use in conjunction with polarization sensitive optical components, polarization multiplexed lightwave transmission systems, and/or coherent communication systems.

FIGURE 12 is a block diagram showing an exemplary embodiment of a polarization multiplexing system 1800. To meet the ever increasing bandwidth demands of current and future communication systems, optical communication systems often communicate information using multiple wavelengths multiplexed into one or several optical

signals. Current filter technology often becomes a limiting factor in the number of optical wavelengths that can be communicated in any given signal. For example, a filter at the receiving end of the transmission system should be capable of at least substantially isolating each wavelength carrying information from its neighboring wavelengths. Current filter technology often limits the density of wavelengths that can be packed into any given signal. One way of increasing the density of wave division multiplexed signals is to alternately polarize neighboring wavelengths so that each wavelength is polarized orthogonally to its neighboring wavelength. A polarization controller can then be used to aid in the filtering at the receiving end of the transmission line to isolate each wavelength from its neighboring wavelengths. In this way, polarization controllers can be used to increase the spectral efficiency of the communication system.

System 1800 shown in FIGURE 12 provides another example of an application for an array of polarization controllers useful in controlling the polarization of individual wavelength signals of a wavelength division multiplexed signal. System 1800 includes a first source bank of transmitters 1802 and a second source bank of transmitters 1804. First and second banks of transmitters may comprise any devices operable to generate optical signals having different wavelengths. In this example, first source bank 1802 generates odd wavelengths λ_1 - λ_n , while second source bank 1804 generates even wavelengths λ_2 through λ_{n+1} . In this example, λ_2 has neighboring wavelengths λ_1

5 Wavelength division multiplexers 806 and 808 are
coupled to first source bank 802 and second source bank
804, respectively. Wavelength division multiplexers 1806
and 1808 each multiplex the individual wavelength signals
received into a multiple wavelength signal 1812 and 1814,
10 respectively.

System 1800 also includes a polarization beam splitter 1816, which receives multiple wavelength signals 1812 and 1814, and orthogonally polarizes those signals for transmission over the principle modes of polarization of an optical communication link 1820. Optical communication link 1820 may comprise a number of lengths of optical fiber, and may include one or more amplifier stages 1822a-1822n as pre-amplifiers, post-amplifiers, and/or inline amplifiers to communication link 1820. System 1800 further includes a wave division demultiplexer 1824 coupled to optical communication link 1820. Wave division demultiplexer 1824 receives multiple wavelength signals 1812 and 1814 communicated over the principle modes of polarization of communication link 1820, and separates the individual wavelength signals. In a particular embodiment, System 1800 may include filters 1826a-1826n. Filters 1826 operate to at least substantially isolate the desired wavelength signal from its neighboring wavelength signals. System 1800 also includes an array of polarization controllers 1810. Each polarization controller of array 1810 operates to provide

any necessary adjustment to the state of polarization of the incoming signal wavelength to facilitate a polarization selection element separating the neighboring orthogonally polarized wavelengths.

5 In a particular embodiment, array 1810 is similar in structure and function to array 810 described in FIGURE 10b. Each polarization controller of array 1810 comprises a plurality of phase shift stages, where at least one of the phase shift stages shares a beam
10 splitter with another of the phase shift stages, such as in polarization controller 610a shown in FIGURE 7b. In one particular embodiment, each polarization controller of array 1810 may comprise three phase shift stages, where all phase shift stages share a common beam
15 splitter, such as in polarization controller 610b shown in FIGURE 7c.

In one particular example, each of the phase shift stages may, for example, include MEMS-based devices, such as those shown in FIGURES 3a-3c, operable to undergo a
20 substantially piston-like motion to introduce a phase shift between copies of the optical signal being phase shifted. Each polarization controller of array 1810 operates to control polarization of one wavelength signal. By implementing an array of polarization
25 controllers, such as shown in FIGURE 10b, the invention facilitates processing of densely packed wavelengths at a small incremental cost over the cost of processing a single wavelength.

In addition, system 1800 includes a plurality of
30 polarization selection elements 1828a-1828n. In a particular embodiment, each polarization selection

09746829-12200

5 System 1800 also includes an array 1830 of
detectors. Array of detectors 1830 operates to receive
optical signals from polarization selection elements 1828
and to form electrical signals 1834a-1834n, which can be
fed to array 1832 of control circuitry. Control
10 circuitry array 1832 may comprise, for example,
electronic control circuitry operable to receive feedback
signals from polarization selection elements 1428 and to
generate control signals 1836a-1836n operable to effect
an adjustment of polarization controllers 1810.
15 Receivers 1840a-1840n receive individual wavelength
signals from polarization selection elements 1828.

25 Polarization beam splitter 1816 receives the
multiple wavelength optical signals and communicates each
signal along a separate principle mode of polarization of
an optical fiber 1820. Wavelength division demultiplexer
1824 receives the multiple wavelength signals and
30 separates the individual wavelength signals therefrom.

Each polarization controller of array 1810 of polarization controllers receives one of the wavelength signals and adjusts the state of polarization of that wavelength signal to assist in separating that wavelength signal from its neighboring wavelength signals. Filters 1826 and polarization selection elements 1828 at least substantially isolate the individual wavelength signal from any remnants of neighboring wavelength signals, and communicate the individual wavelength signals to receivers 1840.

Control array 1832 receives input from polarization selection elements 1828 and generates control signals 1836, which are communicated to polarization controllers of array 1810. These control signals facilitate adjustment of the state of polarization of the incoming wavelength signals to ensure that those signals can be identified distinctly from neighboring wavelength signals.

FIGURE 13 is a block diagram of an exemplary system 1900 operable to facilitate coherent optical communication. Coherent optical communication typically involves combining an optical signal carrying desired information (an incident signal) with a higher power signal from a local oscillator to create a cross product of the two signals, which is of higher power than the incident signal. By substantially matching the phases of the incident signal with the local oscillator signal, the power of the cross product can be maximized and made significantly larger in magnitude than the incident signal. The cross product portion of the signal is more easily detectable than the incident signal, thus

increasing the sensitivity of the optical system and increasing the system's tolerance to noise.

The equation below mathematically illustrates the operation of a coherent optical system, such as system 1900.

$$I_{ph} = R[P_{inc} + P_{loc} + 2(P_{inc}P_{loc})^{\frac{1}{2}} \cos(w_{inct} - w_{loct})]$$

In this equation, I_{ph} is the intensity of the combined signal received at the photo-detector; R is the responsibility of the photo-detector; P_{inc} is the power of the incident signal; and P_{loc} is the power of the local oscillator signal. Because the local oscillator signal is known, it can easily be filtered from the output signal. By using a local oscillator signal having a power that is significantly larger than the power of the incoming signal, the cross product term of this equation — assuming the incident signal and local oscillator signal have substantially equal polarizations — will overwhelm the power of the incident signal, such that the incident signal can be ignored compared to the cross product.

Because the polarization of the incident signal can vary over time, it is desirable to implement a polarization controller to ensure that the incident signal is not orthogonally polarized to the local oscillator signal. Thus, coherent optical communication systems provide another application for polarization controllers.

System 1900 shown in FIGURE 13 illustrates a generic example of a system for providing coherent optical

0574683 12200
002221 2224650

communication. This example shows an embodiment of a system operable to facilitate coherent optical communication of multiple wavelength signals 1902a-1902n (λ_1 - λ_n). System 1900 includes an optical mixer 5 1906 for each wavelength signal 1902a-1902n. Each optical mixer receives an incident wavelength signal 1902 from a wavelength division demultiplexer 1903, and a local oscillator signal 1904 from a local oscillator 1912. Optical mixers 1906 combine incident wavelength 10 signals 1902 with local oscillator signals 1904, and communicate the combined signal to a photo-detector 1908. Local oscillators 1912 reside in feedback loops 1920 between photo-detectors 1908 and optical mixers 1906.

Coherent system 1900 may comprise a homodyne or a 15 heterodyne system. In a homodyne system, the frequencies of the incident signal and the local oscillator signal are approximately equal. In that case, the output of photo-detector 1908 carries the phase difference information of the incident signal and the local 20 oscillator signal. Where coherent system 1900 comprises a homodyne system, local oscillator may be preceded by, for example a loop filter operable to generate an output that drives the local oscillator. In addition, these systems may implement an isolator downstream from the 25 local oscillator to ensure that optical signals are not fed back to the local oscillator.

Heterodyne systems are those in which the frequency of the incident signal and the local oscillator signal differ by a frequency generally referred to as the 30 "intermediate frequency." Heterodyne systems may implement, for example, an intermediate frequency filter

002227 2289460

between the photo-detector and the local oscillator. The output of the intermediate frequency filter is used to drive an automatic frequency controller coupled between the intermediate frequency filter and the local
5 oscillator. The automatic frequency controller generates an output that is proportional to the difference of the frequency of the intermediate frequency filter output and a desired intermediate frequency value. This signal can be used to maintain the frequency difference between the
10 local oscillator output and the received signal.

To help ensure that the incident wavelength signals 1902 and the local oscillator signals 1904 are not orthogonally polarized, system 1900 includes at least one polarization controller for each wavelength signal 1902
15 being processed. In the illustrated embodiment, an array 1910 of polarization controllers may reside within feedback loop 1920 to adjust the state of polarization of the local oscillator signals 1904 relative to the incident wavelength signals 1902. Alternatively, or in
20 addition, an array 1910 of polarization controllers could reside in line with incident wavelength signals 1902, to facilitate adjustment of the state of polarization of those signals relative to the local oscillator signals 1904.

25 In operation, system 1900 receives incident optical wavelength signals at optical mixers 1906, and combines those signals with optical signals 1904 generated by local oscillators 1912. Optical mixers 1906 communicate combined signals to photo-detectors 1908, which generate
30 electrical equivalents of the optical signals received. A control signal derived from the outputs from photo-

detectors 1908 is communicated through feedback loops 1920 to local oscillators 1912 and/or control circuitry coupled thereto. Local oscillators 1912 generate local oscillator signals 1904 in response to the outputs of
5 photo-detectors 1908.

In a particular embodiment, array 1910 of polarization controllers is coupled to local oscillators 1912. Each polarization controller of array 1910 includes, or is coupled to control circuitry operable to
10 determine an adjustment needed to the state of polarization of the local oscillator signal 1904 to ensure that incident wavelength signal 1902 is not polarized orthogonally to local oscillator signal 1904. Polarization controllers of array 1910 can then adjust
15 the state of polarization of the local oscillator signals 1904 to more closely align with the state of polarization of the corresponding incident wavelength signals 1902. As discussed above, array 1910 could alternatively, or in addition reside in line with incident wavelength signals
20 1902 and operate to adjust the state of polarization of those signals.

Each array of polarization controllers could be similar in structure and function to array 810 shown in FIGURE 10b. In that embodiment, each polarization
25 controller of array 1910 comprises a plurality of phase shift stages, where at least one of the phase shift stages shares a beam splitter with another of the phase shift stages, such as in polarization controller 610a shown in FIGURE 7b. In one particular embodiment, each
30 polarization controller of array 1810 may comprise three phase shift stages, where all phase shift stages share a

003327 2294260

common beam splitter, such as in polarization controller 610b shown in FIGURE 7c. System 1900 may be particular well suited to this type of polarization controller, since the state of polarization of the local oscillator is known.

In one particular example, each of the phase shift stages may, for example, include MEMS-based devices, such as those shown in FIGURES 3a-3c, operable to undergo a substantially piston-like motion to introduce a phase shift between copies of the optical signal being phase shifted. By implementing an array of polarization controllers, such as shown in FIGURE 10b, the invention facilitates processing of multiple wavelengths at a small incremental cost over the cost of processing a single wavelength.

V. Gain Equalization in Multiple-Wavelength Optical Signals

FIGURE 14a is a block diagram of an exemplary embodiment of a multiple channel communication system 1000 having gain equalization capabilities. Existing systems have used the conventional ("C") band of wavelengths to communicate optical signals. With the increasing demand for bandwidth, the capacity of communication systems is being expanded by the addition of new communication bands. System 1000 utilizes not only the C-band 1012 of wavelengths, but also the long wavelength ("L") band 1024 and the short wavelength ("S") band 1026. In this embodiment, each band 1012-1016 is approximately 40 nanometers wide. Other bandwidths could be utilized consistent with the invention.

System 1000 includes an optical fiber 1010 operable to communicate a plurality of wavelength bands 1012, 1014, and 1016. In the illustrated embodiment, each band 1012-1016 is amplified using one of optical amplifiers 1022-1026, respectively. Optical amplifiers 1022-1026 may comprise, for example, thulium-doped amplifiers, Raman amplifiers, and/or rare-earth doped amplifiers, such as erbium-doped amplifiers.

As additional bands are added to a communication system, the net power of the fiber is increased. The invention recognizes that when multiple bands of wavelength are communicated using a single system, longer wavelength signals tend to rob energy from shorter wavelength signals. As a consequence, it is desirable to introduce additional attenuation for longer wavelength signals to compensate for the introduced gain tilt. System 1000 addresses this need by including a gain equalizer 1030, which comprises a device operable to provide variable attenuation to one or more selected wavelengths.

In a particular embodiment, a single gain equalizer 1030 is coupled to the outputs of a plurality of amplifiers 1012-1016 in parallel. System 1000 provides an advantage of compensating for gain tilt in a multiple channel system, while maintaining an acceptable signal to noise ratio. By coupling gain equalizer 1030 to the output side of amplifiers 1012-1016, system 1000 avoids attenuating the inputs to amplifiers 1012-1016, which would degrade the signal to noise ratio.

In operation, system 1000 receives optical signal 1010 comprising a plurality of wavelength bands 1012-

09746832 122200

1016. Each of wavelength bands 1012-1016 is passed through a respective optical amplifier 1022-1026, where the optical signals are amplified. Gain equalizer 1030 receives amplified optical signals from amplifiers 1022-1026, and attenuates the signals on a per wavelength basis. In a particular embodiment, gain equalizer 1030 attenuates longer wavelength signals more than shorter wavelength signals to adjust for a gain tilt caused by the longer wavelength signals robbing energy from shorter wavelength signals.

FIGURE 14b is a block diagram of another exemplary embodiment of a multi-channel communication system 1100 having gain equalization capabilities. System 1100 includes an optical fiber 1110 operable to communicate a plurality of wavelength bands 1112, 1114, and 1116. In the illustrated embodiment, each band 1112-1116 is amplified using one of multiple stage optical amplifiers 1122-1126, respectively. Each optical amplifier 1122-1126 comprises a plurality of stages; in this example two stages. Each amplifier 1122-1126 may comprise, for example, thulium-doped amplifiers, Raman amplifiers, and/or rare-earth doped amplifiers, such as erbium-doped amplifiers.

In the illustrated embodiment, system 1100 includes gain amplifiers 1030a-1030c coupled intermediate two stages of each of the multi-stage amplifiers 1022-1026. Implementing a gain equalizer for each of the bands 1112 provides an advantage of facilitating optimization of each gain equalizer for a more narrow range of wavelengths. Moreover, coupling gain equalizers between stages of the multi-stage amplifiers provides an

advantage of maintaining an acceptable optical signal-to-noise ratio, while reducing the risk of saturating optical amplifiers.

FIGURE 14c is a block diagram of one example of a gain equalizer 1200 suitable for use in a single band communication system or a multiple band communication system. In this embodiment, gain equalizer 1200 comprises a phase-shift based gain equalizer operable to provide variable gain or attenuation on a per-wavelength basis by introducing interference between two instances of the optical signal. Gain equalizer 1200 includes a wavelength demultiplexer 1280 operable to receive optical signal 1260 and to separate optical signal 1260 into a plurality of wavelengths 1260a-1260n. Gain equalizer 1200 further includes a wavelength multiplexer 1290 operable to receive processed versions of wavelengths 1260a-n and to multiplex those wavelengths into one or more optical output signals 1272.

In some cases, optical input signal 1260 may comprise wavelengths that need not be processed by gain equalizer 1200. In particular embodiments, gain equalizer 1200 includes a bypass 1275 coupled between demultiplexer 1280 and multiplexer 1290. Bypass 1275 facilitates communication of selected wavelengths between demultiplexer 1280 and multiplexer 1290 without the need to process those signals. Gain equalizer 1200, therefore, provides an advantage in systems, such as metro communication systems, which may use multiple wavelengths, but not require processing of all wavelengths all of the time.

In this example, gain equalizer 1200 comprises a plurality of phase shift stages, each operable to receive one wavelength 1260 and to introduce attenuation or gain into that wavelength depending on a phase shift operating
5 on that signal 1260. Although the phase shift stages shown in FIGURE 14c have a similar configuration to those shown in FIGURE 2a, other configurations could be implemented, such as those shown in FIGURES 1c-1d.

In this example, each phase shift stage receives
10 from a first beam splitter 1220a a first copy 1262 and a second copy 1264 of its associated wavelength 1260. Each phase shift stage includes at least a first mirror 1230 and a second mirror 1240, operable to receive the first and second signal copies 1262 and 1264, respectively.

At least one of first and second mirrors 1230 and
15 1240 comprises a moveable mirror operable to change its position relative to first beam splitter 1220 to create a change in the length of the signal path traveled by first signal copy 1262 relative to the length of the signal
20 path traveled by second signal copy 1264. This change in signal path length corresponds to a phase shift between the two signal copies, which results in an interference when the signal copies are combined at a second beam splitter 1250. System 1200 may implement any moveable
25 mirror structure, such as one of the moveable mirror structures described with respect to FIGURES 3a-3c. By controlling the amount and direction that each mirror 1230 and/or 1240 is moved, system 1200 facilitates variable gain or attenuation of each wavelength 1260a-
30 1260n of signal 1260.

Using micro-electro-optic system (MEMS) based mirrors, such as those described with respect to FIGURES 3a-3c, provides an advantage of facilitating large scale replication of each phase shift stage. For example, each plurality of first mirrors 1230 could be simultaneously formed on a single semiconductor substrate 1295. Likewise, each plurality of second mirrors 1240 could be simultaneously formed on a single semiconductor substrate. One aspect of the invention, therefore, facilitates construction of gain equalizers capable of processing numerous wavelengths for a small incremental cost over a single stage of attenuators. This aspect of the invention provides significant cost savings in processing signals carrying information on multiple channels or wavelengths.

FIGURE 15 is a flowchart showing one example of a method 1300 of facilitating gain equalization of an optical signal having a plurality of wavelengths. The method 1300 begins at step 1310 where gain equalizer 1200 receives optical signal 1260 and separates wavelengths 1260a-1260n at step 1320. This may include, for example, demultiplexing input signal 1260 into its constituent wavelengths.

Gain equalizer 1200 may bypass wavelengths that do not need to be processed by communicating those wavelengths over bypass 1275. Other wavelengths are communicated to one or more first beam splitters 1220 of each attenuator of equalizer 1200 at step 1330. Beam splitters 1220 of each attenuator communicate a first copy of the input wavelength 1262 toward first mirrors 1230 at step 1350, and communicate a second copy 1264

Table 1. Demographic characteristics of the study population	
Age (years)	65.0 ± 10.0
Gender	
Male	50 (50.0%)
Female	50 (50.0%)
Education (years)	12.0 ± 2.0
Marital status	
Married	40 (80.0%)
Single	10 (20.0%)
Occupation	
Retired	30 (60.0%)
Unemployed	20 (40.0%)
Income (USD/month)	1,200 ± 300
Health insurance	
Yes	45 (90.0%)
No	5 (10.0%)
Comorbidities	
Hypertension	35 (70.0%)
Diabetes	25 (50.0%)
Cholesterol	20 (40.0%)
Smoking status	
Smoker	15 (30.0%)
Non-smoker	35 (70.0%)
Alcohol consumption	
Yes	10 (20.0%)
No	40 (80.0%)

In any case, components of the wavelength signal copies are combined at step 1380 to generate an output wavelength signal that varies in amplitude from the input wavelength signal 1260 due to a phase shift caused by the piston-like movement of one or more moveable mirror layers of mirrors 1230 and/or 1240.

VI. Optical Add/Drop Multiplexing

FIGURE 16a is a block diagram showing one embodiment of an exemplary system 1400 operable to perform wave division add/drop multiplexing. System 1400 includes a wave division demultiplexer 1410 operable to receive an optical signal 1460 and to separate optical signal 1460 into a plurality of wavelengths 1460a-1460n. System 1400 further includes a wavelength multiplexer 1490 operable to receive processed versions of wavelengths 1460a-n and

to multiplex those wavelengths into one or more optical output signals 1472.

System 1400 further comprises an array 1445 of MEMS-based optical add/drop multiplexers, each operable to facilitate add/drop multiplexing of one of wavelengths 1460a-n. In a particular embodiment, MEMS array 1445 may comprise an array of MEMS having moveable mirror structures operable to be displaced in an at least substantially piston-like motion to create an interference between two substantial copies of the wavelength signal. Implementing array 1445 using MEMS-based arrays facilitates wave-division add/drop multiplexing on any number of wavelengths 1460a-n at a small incremental cost over facilitating add/drop multiplexing for a single wavelength signal. As a result, system 1400 provides a cost effective mechanism for wave-division add/drop multiplexing large numbers of wavelengths.

In some cases, optical input signal 1460 may comprise wavelengths that need not be processed by array 1445. In particular embodiments, system 1400 includes a bypass 1475 coupled between demultiplexer 1410 and multiplexer 1490. Bypass 1475 facilitates communication of selected wavelengths between demultiplexer 1410 and multiplexer 1490 without the need to process those signals. System 1400, therefore, provides an advantage in systems, such as metro communication systems, which may use multiple wavelengths, but not require processing of all wavelengths all of the time.

In operation, system 1400 receives input signal 1460 and demultiplexes that signal into a plurality of

wavelength signals 1460a-1460n. Some of wavelengths 1460a-n may be routed over bypass 1475, while others are directed toward array 1445 of MEMS-based add/drop multiplexers. MEMS-based add/drop multiplexers receive
5 wavelengths 1460a-n and may drop the received wavelength in favor of an added wavelength signal to replace the dropped wavelength. Processed wavelengths 1460a-n and bypassed wavelengths 1460a-n are then combined at wavelength division multiplexer 1490 and communicated as
10 output signal 1472.

FIGURE 16b is a block diagram showing one particular example of a MEMS-based add/drop multiplexer (ADM) 1405. In the illustrated embodiment, ADM 1405 is similar in structure and operation to two-by-two switch 310 shown in
15 FIGURE 5b. The invention is equally applicable to other configurations, such as that shown in FIGURE 1c.

ADM 1405 includes a first beam splitter 1420, which receives both an input optical signal 1461, as well as an added signal 1465. Beam splitter 1420 generates a first
20 copy and a second copy of both input signal 1461 and added signal 1465. ADM 1405 communicates the first copies along a first signal path 1462 and the second copies along a second signal path 1464. A first mirror 1430 receives first signal copies from signal path 1462
25 and reflects those signal copies toward an output, in this case second beam splitter 1450. A second mirror 1440 receives second signal copies from signal path 1464 and reflects those signal copies toward an output, in this case second beam splitter 1450. The reflected first
30 and second signal copies are combined at the output, in this case a second beam splitter 1450.

By changing the position of one or more of the mirrors 1430 and 1440 residing between the input and the output of the phase shifter, a phase shift is introduced between the first and second signal copies. By
5 introducing a particular phase shift, ADM 1405 can facilitate pass through operation, or add/drop operation. In a pass through mode of operation, ADM 1405 operates to communicate input signal 1461 to an output 1472 for further transmission. In an add/drop mode, ADM 1405
10 operates to drop input signal 1461 at drop output 1474, and to communicate added signal 1465 to output 1472 for transmission in lieu of input signal 1461.

Some or all of mirrors 1430 and 1440 can comprise moveable mirror structures operable to vary their
15 positions to result in a change in the length of the path of and phase difference between first and/or second signal copies communicated along signal paths 1462 and 1464. For example, the intensity of transmitted output signal 1472 is proportional to \cos^2 of one half of the
20 phase difference between first and second signal copies of the input signal 1461, and the \sin^2 of one half of the phase difference between the first and second copies of added signal 1465. Likewise, the intensity of dropped output signal 1474 is proportional to \sin^2 of one half of
25 the phase difference between first and second signal copies of the input signal 1461, and the \cos^2 of one half of the phase difference between the first and second copies of added signal 1465.

Therefore, when there is no phase difference (or a
30 phase difference of 2π , or an even multiple thereof) input signal 1461 is communicated as transmitted output

002221 2284250

1472. Where there is a π (or odd multiple of π) phase difference,, input signal 1461 is dropped at drop output 1474, and added signal 1465 is communicated over transmitted output 1472. By varying the positions of
5 mirrors 1430 and/or 1440 to switch between a phase difference of, for example, approximately zero and π , ADM 1405 facilitates either passing input signal 1461 through to transmitted output 1472, or dropping input signal 1461 in favor of added signal 1465 for
10 transmission over transmitted output 1472.

Although the illustrated embodiment shows just one MEMS device in each arm of the phase shifter, additional MEMS devices could be implemented without departing from the invention. Furthermore, although MEMS devices 1430
15 and 1440 are shown at an approximately forty-five degree grazing angle, these devices could be located at other grazing angles to the signals being reflected.

FIGURE 16c is a block diagram showing another example of a MEMS-based add/drop multiplexer (ADM) 1500.
20 In the illustrated embodiment, ADM 1500 includes a drop phase shift stage 1505 that is separate from an add phase shift stage 1510. This embodiment may be particularly useful, for example, where it is desired to reduce or eliminate interference between input and added signals
25 that would otherwise traverse the same phase shift stage.

In this example, drop phase shift stage 1505 receives an optical input signal 1560 and operates to either communicate signal 1560 to add phase shift stage 1510, or to drop signal 1560 from the circuit. Add phase
30 shift stage 1510 operates to either input signal 1560 from drop phase shift stage 1505 or to receive an added

05746822 132300

In this example, add phase shift stage 1505 includes a beam splitter 1520a, which receives input signal 1560 and sends a first signal copy 1562a toward a first mirror 1530a, and a second signal copy 1564a toward a second mirror 1540a. First and second mirrors 1530a and 1540a reflect first and second signal copies 1562a and 1564a toward a second beam splitter 1550a. In this embodiment, second beam splitter 1550a combines components of the reflected first and second signal copies 1562a and 1564a to form output signals 1572a and 1574a.

Some or all of mirrors 1530 and 1540 can comprise moveable mirror structures operable to vary their positions to result in a change in the length of the path of and phase difference between first and/or second signal copies 1562 and 1564. By varying the positions of mirrors 1530a and/or 1540a to switch between a phase

difference of, for example, approximately zero and π , drop phase stage 1505 facilitates switching between passing input signal 1560 through stage 1505 and dropping signal 1560 from stage 1505. Similarly, by varying the positions of mirrors 1530b and/or 1540b to switch between a phase difference of, for example, approximately zero and π , drop phase stage 1505 facilitates outputting either pass through signal 1574, or added signal 1565 at output 1576.

Although this embodiment shows pass-through operation between stages over output 1574 and drop operation over port 1572, add/drop multiplexer could be reconfigured to communicate pass-through signals from port 1572 to port 1565 and drop signals from port 1574. In that embodiment, signals would pass through from the drop stage to the add stage at port 1572 where mirrors 1530a/1540a are positioned to provide a π phase shift, and would be dropped at port 1574 where those mirrors were positioned to provide no phase shift. Likewise, the input signal would pass through add stage to output 1576 where mirrors 1530b/1540b are positioned to create a π phase shift, whereas added signal 1565 would pass to output 1576 where those mirrors create no phase shift.

In operation, ADM 1500 receives input signal 1560 at beam splitter 1520a and communicates a first signal copy 1562a toward first mirror 1530a and a second signal copy 1564a toward second mirror 1540a. Mirrors 1530a and 1540a reflect first and second signal copies 1562a and 1564a toward beam splitter 1550a, which operates to combine components of those signals to generate an output signal. Depending on the position of mirrors 1530a

002227 228460

and/or 1540a, drop phase shift stage 1505 will either pass input signal 1560 toward add phase shift stage 1510, or will drop input signal 1560 at output 1572, sending no signal to add phase shift stage 1510.

5 Add phase shift stage 1510 either receives pass through input signal 1574 from drop phase shift stage 1505, or receives added signal 1565. Mirrors 1530b and/or 1540b are then positioned to pass the received signal to output 1576. For example, in this embodiment
10 if add phase shift stage 1510 receives a pass through signal 1574, mirrors 1530b and/or 1540b are positioned to introduce approximately no phase shift (or a multiple of 2π phase shift) between signal copies 1562b and 1564b to result in pass through signal 1574 being communicated
15 through output 1576. On the other hand, if add phase shift stage instead receives added signal 1565, mirrors 1530b and/or 1540b are positioned to introduced an approximately π (or odd multiple of π) phase shift between signal copies 1562b and 1564b to result in added
20 signal 1565 being communicated through output 1576.

FIGURE 16d is a block diagram showing a plurality of add/drop multiplexers as shown in FIGURE 16b arranged to collectively form a wave division add/drop multiplexer 1600. In this example, each ADM of array 1610 is similar
25 to that shown in FIGURE 16c. Of course, an array of add/drop multiplexers could likewise be formed from add/drop multiplexers such as those shown in FIGURE 16b.

In the illustrated embodiment, each drop phase shift stage includes two arms, at least one of which comprises
30 a moveable mirror structure 1630a and/or 1640a. Mirrors 1630a and/or 1640a are operable to move in response to

09746921.12200

5

10

20

30

formed on a single semiconductor substrate. Likewise, each plurality of second mirrors 1540 could be simultaneously formed on a single semiconductor substrate. One aspect of the invention, therefore, facilitates construction of add/drop multiplexers capable of processing numerous wavelengths for a small incremental cost over a single stage add/drop multiplexer. This aspect of the invention provides significant cost savings in processing signals carrying information on multiple channels or wavelengths.

FIGURE 17 is a flowchart showing examples of a method 1700 of facilitating optical add/drop multiplexing. Steps 1705 through 1730 describe a method 1702 applicable to both single phase shift solutions as well as embodiments using separate phase shift stages for add and drop operations.

In an embodiment using one phase shift stage to facilitate both pass-through operation and add/drop operation, the method 1700 begins at step 1705 where optical add/drop multiplexer (ADM) 1405 receives an optical input signal 1461. This may include, for example, receiving from a wave division multiplexer one wavelength of an optical signal at a beam splitter 1420. This may further include receiving an added signal 1465 at beam splitter 1420. ADM 1405 generates copies of the signals received by beam splitter 1420 at step 1710 and communicates, at step 1715, those copies toward first and second mirrors 1430 and 1440, respectively.

Depending on the desired function, ADM 1405 may position one or more of the mirrors to contribute to phase shift between the first and second signal copies.

This may include, for example, one or both of mirrors 1430 and 1440 receiving control signals operable to cause a moveable mirror element to move toward an inner conductive layer.

- 5 Through the use of moving mirror elements, ADM 1405 can introduce a phase shift sufficient to either pass input signal 1461 transmitted output 1472, or to drop input signal 1461 in favor of added signal 1465, which will then be communicated from transmitted output 1472.
- 10 For example, mirrors 1430 and/or 1440 can introduce no phase shift (or a multiple of 2π) between the signal copies, causing input signal 1461 to pass toward transmitted output 1472 at step 1735. Alternatively, mirrors 1430 and/or 1440 can introduce a π (or odd
- 15 multiple of π) phase shift at step 1725 to cause input signal 1461 to be dropped at output 1474. In that case, added signal 1465 is communicated as transmitted output 1472 at step 1730. Of course, the locations of input for input signal 1461 and added signal 1465 could be flipped
- 20 without departing from the invention. In that case, a π (or odd multiple of π) phase difference would cause the input signal 1461 to be communicated at output 1472, while a zero (or 2π , or multiple of 2π) phase difference would cause added signal 1465 to be
- 25 communicated as output 1472.

- Steps 1705 through 1730 are also applicable to an embodiment using separate phase shift stages for the add and drop operations. In that case, the method 1700 begins at step 1705, where optical add/drop multiplexer
- 30 (ADM) 1500 receives an optical input signal 1560. This may include, for example, receiving from a wave division

5

10

20

30

101

at step 1745. Again depending on the configuration and signal processing desired, ADM 1500 can positions one or more of the mirrors 1530b and/or 1540b to contribute to phase shift between the first and second signal copies.

5 This may include, for example, one or both of mirrors 1530b and 1540b receiving control signals operable to cause a moveable mirror element to move toward an inner conductive layer.

ADM 1500 can introduce a phase shift sufficient to
10 either pass input signal 1560 toward output 1576, or to pass added signal 1565 to output 1576. For example, mirrors 1530b and/or 1540b can introduce no phase shift (or a multiple of 2π phase shift) between the signal copies, causing input signal 1560 to pass to output 1576
15 at step 1765. Alternatively, mirrors 1530b and/or 1540b can introduce π (or odd multiple of π) phase shift at step 1755 to cause added signal 1565 to be output at step 1760. Of course, the phase shifts discussed herein are for exemplary purposes only. Other configurations could
20 use other phase shift combinations to achieve the desired signal processing consistent with the invention.

These steps can be duplicated at each add/drop multiplexer in an array of add/drop multiplexers to facilitate processing of any number of individual
25 wavelength signals. This aspect of the invention provides a significant advantage in providing cost effective signal processing in multiple wavelength systems.

Although various aspects of the present invention
30 have been described in several embodiments, a myriad of changes, variations, alterations, transformations, and

002222 222222 122200

5 the appended claims.

Figure 1 displays a series of 12 plots showing the evolution of various physical quantities over time t (ranging from 0 to 10^5 s). The plots are arranged in two columns. The left column shows: 1. Temperature T (K) vs t (s), 2. Density ρ (g/cm³) vs t (s), 3. Velocity v (km/s) vs t (s), 4. Pressure P (dyn/cm²) vs t (s), 5. Magnetic field B (G) vs t (s), 6. Ionization fraction X vs t (s), 7. Ionization fraction X vs t (s), 8. Ionization fraction X vs t (s). The right column shows: 9. Ionization fraction X vs t (s), 10. Ionization fraction X vs t (s), 11. Ionization fraction X vs t (s), 12. Ionization fraction X vs t (s). Each plot has a logarithmic y-axis and a linear x-axis from 0 to 10^5 s. The plots show the evolution of these quantities during the recombination of a gas, with various curves representing different models or parameters.